Assessment of Hand Function Through the Coordination of Contact Forces in Manipulation Tasks

by

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Exploration of force coordination has been one of the most often used approaches in studies of hand function. When holding and manipulating a hand-held object healthy individuals are typically able to highly coordinate the perpendicular (grip force; GF) with the tangential component of the contact force (load force; LF). The purpose of this review is to present the findings of our recent studies of GF-LF coordination. Regarding the mechanical factors affecting GF-LF coordination, our data suggest that both different hand segments and their particular skin areas could have markedly different friction properties. It also appears that the absolute, rather than relative safety margin (i.e., how much the actual GF exceeds the minimum value that prevents slipping) should be a variable of choice when assessing the applied magnitude of GF. The safety margin could also be lower in static than in free holding tasks. Regarding the involved neural factors, the data suggest that the increased frequency, rather than an increased range of a cyclic LF could have a prominent detrimental effect on the GF-LF coordination. Finally, it appears that the given instructions (e.g., 'to hold' vs. 'to pull') can prominently alter GF-LF coordination in otherwise identical manipulation tasks. Conversely, the effects of handedness could be relatively weak showing only slight lagging of GF in the non-dominant, but not in the dominant hand. The presented findings reveal important aspects of hand function as seen through GF-LF coordination. Specifically, the use of specific hand areas for grasping, calculation of particular safety margins, the role of LF frequency (but not of LF range) and the effects of given instructions should be all taken into account when conducting future studies of manipulation tasks, standardizing their procedures and designing routine clinical tests of hand function.

Key words: grip force, load force, coupling, scaling, modulation.

Introduction

Human hand is a 'tool' routinely used to interact with almost all objects in our physical environment. It can perform a wide variety of actions from brittle and gentle, such as feeding, carving a tool and caressing, to a heavy labor, such as using a tool to fight or to lift heavy objects. A skilled use of hands can be considered as the most important among our motor abilities since marked impairment of the hand function brings the heaviest burden to the daily life. Specifically, even a mild dysfunction in the

control of manipulative actions seriously affects one's independent living. Therefore, the hand function has been studied through a variety of approaches, such as behavioral, kinematic, kinetic, electromyographic etc. Each of those approaches gives its specific insight into the neural control of manipulative actions. Within this study, we selected the kinetic approach which can be based on a frequently used simple model of mechanical interaction between the hand and the hand-held object. Moreover, the kinetic variables routinely used in the studies of hand function have proven to be valid measures of

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mechanical and control properties of manipulative actions (Johansson and Westling, 1984; de Freitas et al., 2008a). Finally, note that the same variables proved to be sensitive to detect the differences in hand function between healthy subjects and the individuals known for impaired hand function, such as the neurological patients (Nowak and Hermsdorfer, 2006; Krishnan et al., 2008; Krishnan and Jaric, 2008).

Mechanics and neural control of manipulation

An object can be manipulated in a variety of ways depending on task requirements. For example, one can apply a precision grip (i.e., only the finger tips are in the contact with the object) while holding a champagne glass, a power grip (entire ventral part of the hand is used) when using a hammer, or a two-hand power grip when manipulating large and heavy objects. Regardless of the grip type, one has to apply a certain magnitude of force perpendicularly to the grasping sides of the object to prevent a slippage caused by tangential forces that can originate either from the object's weight and inertia, or from external reaction forces. The perpendicular

(i.e., normal) force applied against the object surface will be referred to as grip force (GF), while the tangential force acting in parallel to the object's contact surface will be referred to as load force (LF).

According to a routinely used simple mechanical model of holding a vertically oriented object (Johansson and Westling, 1984), the minimum GF (GF_{min}) has to be at least equal to the ratio between LF and the static coefficient of friction (COF) between the digits and the object surface in order to prevent slippage:

$$GF_{min} = LF / COF . \quad (\text{eq. 1})$$

However, during object manipulations individuals inevitably apply GF that is somewhat higher than GF_{min} . Either the absolute or relative difference between the employed GF and GF_{min} required to prevent slippage ($GF - GF_{min}$) has been referred to as the safety margin. It has been shown that the safety margin remains relatively low and stable during object manipulation even when LF is rapidly changing (Johansson and Westling, 1984; Westling and Johansson, 1984).

Figure 1

Illustration of a simple mechanical model of holding a vertically oriented object. Slippage caused by tangential force that originates from the object's weight and inertia (load force; LF) is prevented by reaction force that originates from the perpendicular force (grip force; GF) due to the acting friction. Circles illustrate the tips of the fingers and the thumb.

Keeping a low safety margin has been interpreted as a buffering strategy that keeps GF high enough to maintain stability and prevent accidental slipping of an object and yet keeps GF low enough to prevent both the associated muscle fatigue and crushing the object due to excessive forces. As a result, it has been concluded that the CNS closely monitors the changes in the LF and coordinates the GF in an anticipatory fashion with the LF while performing various manipulation tasks (Johansson and Westling, 1988; Flanagan and Wing, 1995).

Variables used to assess GF-LF coordination

A variety of dependent variables have been used to evaluate the GF-LF coordination in various manipulation tasks. The indices of GF-LF coordination routinely assessed in different tasks have been GF scaling, GF-LF coupling, and GF modulation. Regarding the GF scaling, the GF to LF ratio (GF/LF ratio) has been calculated as the ratio of either the average or peak values of GF and LF. Elaborate GF-LF coordination has been mostly associated with a relatively low and stable GF/LF ratio even during a rapidly changing LF (Johansson and Westling, 1984; de Freitas et al., 2007). Another frequently employed index of GF-LF coordination has been usually referred to as GF-LF coupling. It has been evaluated by the maximum cross-correlation coefficient and the corresponding time lag observed between GF and LF time series (Flanagan and Wing, 1995; Jaric et al., 2006; Danion et al., 2009; de Freitas and Jaric, 2009; Danion et al., 2010). A high coupling has been seen as both the high values of the correlation coefficients observed between GF and LF time series and the time lag between them close to zero. Lastly, GF modulation shows how much GF adapts to the ongoing changes in LF. GF modulation has been routinely assessed through the regression lines obtained from the GF-LF diagrams, where the slope of the regression line represents the GF gain, while the intercept represents the GF offset (Flanagan and Wing, 1995; de Freitas and Jaric, 2009). Both a high value of GF gain and a low value of GF offset have been considered as indices of high GF-LF coordination.

All of the above mentioned indices of GF-LF coordination might show dependency on numerous factors, such as various task variables and conditions, the populations tested and so on.

For example, neurological patients (e.g., individuals with multiple sclerosis, cerebral palsy, Parkinson's disease, and stroke) consistently reveal disrupted force control during object manipulation that usually results in an elevated GF/LF ratio (Nowak and Hermsdorfer, 2005; Krishnan et al., 2008; Krishnan and Jaric, 2008; Mackenzie et al., 2009). Therefore, the studies of GF-LF coordination have been seen as a promising approach for development of quantitative clinical tests of hand function (Jaric et al., 2005a; Nowak and Hermsdorfer, 2006; Krishnan and Jaric, 2008). Aside from the neurological populations, a deteriorated GF-LF coordination has been seen in healthy individuals during performance of presumably complex and demanding tasks, such as when the applied LF continuously changes its direction (Jaric et al., 2005b; de Freitas et al., 2007; Freitas et al., 2007; de Freitas et al., 2008b), when the frequency of LF change is particularly high (e.g., when shaking an object or producing an oscillatory LF against an external support (Flanagan and Wing, 1995; Jaric et al., 2006)), when the actions of two hands are dissimilar (Serrien and Wiesendanger, 2001; Krishnan and Jaric, 2010), or when the visual feedback (Danion et al., 2010) or gravitational field (White et al., 2005) is altered. Although most of these phenomena have been extensively studied, the role of a number of other potentially important mechanical and neural factors still remains largely unexplored. Within the following sections we will present our recent studies aimed towards exploring the role of a several presumably mechanical and neural factors that could affect GF-LF coordination. The expected findings could not only serve for further standardization of the experimental protocols aimed to explore GF-LF coordination, but also for revealing important aspects of neural control of manipulative actions.

Mechanical Factors: Friction

Depending on particular requirements of a manipulation task, we use different grasping techniques that involve not only different hand segments, but also their various skin areas. For example, the pinch and precision grasp (commonly used during precise manipulation of light objects, such as picking up a coin or grasping a champagne glass) involve the tips of the digits and the thumb, while the uni- and bi-manual

power grasps (commonly used during manipulating heavy objects, such as holding a tool or carrying a box) involve large ventral areas of the digits and the palm. When the hand specialization for manipulative actions is considered, one could speculate that the frictional properties of the hand areas that are commonly used during object manipulations (i.e. “specialized” hand areas) might have higher COF than the other hand areas that are not commonly used (i.e. “non-specialized” hand areas). Note that according to the above presented simple model of manipulation (see eq. 1), higher COF allows for a lower GF, which in turn causes less fatigue and allows a better control of the manipulated object (Claudon, 2006; Laroche et al., 2007).

In our recent study we explored various grasping techniques that involve a large number of either specialized (e.g. finger tips, distal and proximal palm) or non-specialized (e.g. fist, wrist) hand areas (Figure 2) and measured the static COF of the hand areas involved in those techniques ((Uygur et al., 2010b); here we present the data from only few out of a larger sample of grasping techniques). Moreover, to test whether COF of different hand areas are also coating specific, we used both rubber and acetate coatings to represent surfaces with high and low COF, respectively. Finally, we used a standard ‘slip point’ method to calculate COF from GF and LF recorded at the instant of slip (Westling and Johansson, 1984; Savescu et al., 2008). Specifically, subjects were instructed to hold the vertically oriented object and to slowly reduce the GF until the object slips. At the time point just prior to the initiation of slipping, we calculated the ratio between the measured GF and the weight of the handle (i.e. slip ratio) and used it to calculate the static COF as:

$$\text{COF} = 1 / (2 \text{ slip ratio}) \quad (\text{eq. 2})$$

Overall, our results revealed that the COF measured from the grasping techniques that involved “specialized” hand areas were higher than those measured from the grasping techniques that involved “non-specialized” hand areas (Figure 3). A higher COF is advantageous especially during heavy object manipulation since it requires less GF and, therefore, reduces the fatigue in the GF producing muscles (Seo et al.,

2008) and decreases risk of hand injuries (Laroche et al., 2007). Moreover, the results revealed that the difference among the hand segments could be coating specific. Another important finding of our study is a high across subject variability of COF obtained from the same skin areas. Overall, the differences found in COF across the hand segments and coatings, as well as a high inter-subject variability of the measured COF strongly emphasizes the importance of routine assessment of COF in the future biomechanical, motor control and ergonomic studies of manipulation activities.

Mechanical Factors: Grasping Techniques and Safety Margin

As already described, when we manipulate objects we routinely employ higher GF than the minimum required. This “excess” grip force has often been referred to as safety margin. Previous research has shown that the safety margin is one of the factors that could be closely monitored by the CNS to provide a relatively low and stable LF (Johansson and Westling, 1984; Westling and Johansson, 1984). The studies of manipulation activities have calculated safety margin either as a relative (i.e. SM_{rel} ; the difference between the applied GF and the GF_{min} in percentage of the GF_{min}) or absolute (i.e. SM_{abs} ; the absolute difference between the applied GF and GF_{min} calculated in N) without exploring their particular properties (Flanagan and Wing, 1995; Jenmalm et al., 1998; Cole et al., 1999; Mrotek et al., 2004). As a consequence, it still remains unknown whether the CNS keeps either SM_{rel} or SM_{abs} invariant across a variety of static and dynamic manipulation tasks, such as those performed with the objects of different frictional properties and manipulated by using different grasping techniques.

We asked healthy young individuals to perform both static and free holding tasks that required exerting the same pulling force (de Freitas et al., 2009). They completed each task under five different grasping conditions (Figure 2) and two different object coatings that provided low and high coefficient of friction (e.g. acetate and rubber, respectively). We specifically analyzed both SM_{rel} and SM_{abs} as a function of friction since their values depend on the GF_{min} which is inversely proportional to the acting COF (see eq. 1). The results revealed a high and positive relationship of SM_{rel} with the acting COF

in both free and static holding tasks (Figure 4A). On the other hand, SM_{abs} revealed no significant relationship with the acting COF in static holding tasks, while a moderately negative relationship was found between SM_{abs} and friction in free holding tasks (Figure 4B). Finally, a lower safety margin was observed in the static than in the free holding condition

Collectively, our results suggest that the CNS could keep SM_{abs} , rather than SM_{rel} as partly invariant among the studied free and static manipulation tasks. Since SM_{abs} was found to be an invariant characteristic of GF control, we

suggest that the future studies of hand function should use SM_{abs} not only when assessing the basic properties of hand function, but also when comparing hand function between healthy individuals and clinical populations. The lower safety margin observed in the static holding task could be interpreted as an acceptance of a higher risk of slipping. Namely, a partial slipping of the hand along an externally fixed object could not have such undesirable consequences as a dropping of the object in a free holding task.

Figure 2

Illustration of the grasping techniques that involve 'specialized' (precision, distal palm and proximal palm grasps) and 'non-specialized' (wrist and fist grasp) segments and skin areas in the contact with the object

Figure 3

Coefficients of friction (COF; means with SD bars) obtained from different grasping techniques separately for a high friction (i.e., rubber) and low friction (silk) coating materials

Figure 4

Relative (SM_{rel} ; A) and absolute (SM_{abs} ; B) safety margin as a function of the acting coefficient of friction. The dashed and solid lines correspond to the free and static holding task, respectively

Neural Factors: LF range and frequency

Humans frequently perform continuous manipulation movements, such as shaking an object vertically or horizontally, using a hammer repetitively to strike a nail, or using an external support to maintain balance during a bus ride. These tasks are presumably controlled by feed-forward neural mechanisms requiring minimal corrections triggered by the sensory information (Flanagan and Wing, 1993; Sternad et al., 2000). To study continuous object manipulations, researchers have commonly used either dynamic tasks (e.g., cyclic arm movements with a hand-held load (Flanagan and Wing, 1995)), or static tasks (e.g., exerting an oscillatory force against an externally fixed device (Jaric et al., 2005a; Jaric et al., 2005b; Jaric et al., 2006; de Freitas and Jaric, 2009; Uygun et al., 2012)). Overall, the results have revealed that an increase in the frequency of an oscillatory task could be associated with a deteriorated GF-LF coordination (Flanagan and Wing, 1995; Jaric et al., 2006). However, this deterioration might not have been caused by the frequency itself, but rather by the increase in the rate of LF change. An oscillatory pattern of LF can be modeled as a sinusoidal function:

$$LF = LF_0 \sin(\omega t), \quad (\text{eq. 3})$$

where LF_0 is LF amplitude, while ω is the angular frequency of LF change.

Therefore, the rate of LF change is

$$dLF/dt = LF_0 \omega \cos(\omega t). \quad (\text{eq. 4})$$

The last equation shows that the rate of LF change can increase not only due to an increase in the LF frequency, but also due to an increase in LF range. Keeping in mind the kinetic generalization of the minimum jerk hypothesis (i.e., when controlling voluntary movements the CNS attempts to minimize the force change (Uno et al., 1989)), one could argue that the CNS tends to minimize the GF change in the tasks that involve a high rate of LF change. A reduced GF change would inevitably lead to a decreased GF modulation and GF-LF coupling, as well as to an increased GF/LF ratio. These changes have been observed in tasks that require a high frequency of LF change (Flanagan and Wing, 1995; Jaric et al., 2006). Therefore, based on the minimum jerk hypothesis and its kinetic generalization, one

could hypothesize that an increase in either LF frequency or LF range would result in a decreased GF-LF coordination.

We asked healthy individuals to exert isometric LF profiles in an oscillatory fashion at 5 different frequencies (i.e., 0.67, 1.33, 2, 2.67, and 3.33 Hz) and within 5 different LF ranges (6, 7.5, 10, 15 and 30 N (Uygur et al., 2010a)). The results revealed a prominent effect of an increase in the LF frequency, but not an increase in LF range, on the coordination between GF and LF. Specifically, GF-LF coupling assessed through the correlations between the GF and LF time series decreased with LF frequency, but not with LF range (Figure 5A). The following panel depicts a similar finding regarding GF modulation (Figure 5B). Namely, GF gain decreases with LF frequency, but not with GF range. The lack of the effect of LF range apparently contradicts the predictions drawn from the kinetic generalization of the minimum jerk hypothesis. One could interpret these findings by the different synergies of GF and LF that could be applied in the phases of the increasing and decreasing LF and GF forces. Therefore, the future studies of hand function should consider task frequency, rather than the force range, when either designing rhythmic manipulation tasks performed under static conditions, or comparing the results of the previous research, or developing the standard tests of hand function. Future studies should explore to which extent the present findings can be generalized to the free movement tasks.

Neural Factors: Instructions and Hand Dominance

Instructions given in various motor control experiments have been shown to affect the studied motor outcome. For example, during a pointing task that requires a discrete and accurate arm movement, the instructions to move “fast”, “fast and accurate”, and “accurate” have distinctive effects not only on the muscle neural activation, but also on the subject's motor performance (Brown and Cooke, 1981). When the kinetic tasks are considered, giving the instructions to produce force as “hard-and-fast as possible” and as “fast as possible” revealed differences in the rate of force development, while the maximum force remained unaffected (Sahaly et al., 2001). Finally, emphasizing the action of particular muscle groups in an kinetically

identical static task leads to different patterns of muscle activation (Latash and Jaric, 1998).

Regarding the role of hand dominance, it has been shown that motor lateralization could be an important factor affecting the neural control of human movements. According to the motor lateralization theory (Sainburg, 2002), the non-dominant hand could be specialized for execution of the feedback dominated tasks, while the dominant hand could be more specialized for performing the dynamic, feed-forward controlled tasks. Although previous research has partly studied the effect of handedness on GF-LF coordination of manipulation tasks (Ferrand and Jaric, 2006; de Freitas et al., 2007), the above hypothesized effect of motor lateralization has never been tested in the context of GF-LF coordination in manipulation tasks when similar movements were performed under different instructions.

We recently conducted an experiment designed to explore the effects of both the instruction and handedness on the performance and GF-LF coordination in static bimanual manipulation tasks (Jin et al., 2011). Subjects were asked to bimanually exert an oscillatory (i.e., approximately sinusoidal) LF profile while holding stationary the system of two mechanically attached handles that was free to move (Figure 6). Since the instructions “to pull” and “to hold” have not only been routinely used in studies of manipulation actions, but also frequently swapped over without paying particular attention to them, we used three different sets of instructions. In particular, we asked the subjects: (1) to “pull” the handles equally with both hands, (2) to “pull” with right hand and to “hold” with left hand, and (3) to “hold” with right hand and to “pull” with left hand. One should keep in mind that due to the nature of the manipulation task (i.e., keeping a free moving device stationary while the hands were either pulling or holding), the exerted LF by two hands had to be the same. Therefore, the tasks were mechanically identical regardless of the given instructions.

The results revealed that the instructions used in manipulation tasks could markedly affect the coordination between GF and LF. Specifically, the instruction to “pull” revealed higher indices of GF-LF coordination through a lower GF scaling

(Figure 7A), higher GF-LF coupling (Figure 7B), and higher GF modulation (Figure 7C), than the instruction to "hold". Note that the results were similar regardless of whether both or only one hand was pulling. Regarding the handedness, the only effect we observed was a somewhat increased time lags between GF and LF in the non-dominant hand (i.e., LF leading GF) when compared to the same time lags obtained from the dominant hand (Figure 7D).

Overall, the observed findings suggest that instructions could have a prominent effect on GF-LF coordination. Therefore, the instructions need to be meticulously planned in the studies of

manipulation activities, particularly when asking participants "to pull" and "to hold". Regarding the effects of handedness, note that the observed time lags were both partly inconsistent and relatively small, particularly when compared with the time needed for voluntary correction of motor acts. Nevertheless, the results suggest a partial involvement of the feedback neural mechanisms in the control of the non-dominant hand. A lack of other effects of handedness could be explained by the predominantly static nature of the tested tasks (Sainburg, 2002) and, therefore, future studies could apply a similar approach to dynamic manipulation tasks.

Figure 5

GF-LF coordination assessed from static manipulation tasks performed across different frequencies (0.67-3.33 Hz) and force ranges (6-30 N). The panels illustrate the averaged across the subjects data regarding the GF-LF coupling (i.e., the median correlation observed between GF and LF; A) and GF gain (slope of the GF-LF regression lines; B)

Figure 6

A schematic illustration of the manipulation condition. A free-moving device consists of 2 mutually attached handles and each of them records the grip (GF) and load force (LF). Circles illustrate positions of fingers and the thumb of the subject's hands. Note that steady holding of the device requires two opposing LF to be equal

Figure 7

GF-LF coordination indices observed in oscillation tasks (data average data across subjects with standard error bars) depending on the given instructions to pull or to hold with particular hand, and to pull with both hands (B/Pull).

Data are presented separately for the dominant and non-dominant hand.

A) GF scaling assessed by the GF/LF ratio.

B) GF-LF coupling assessed by correlation coefficients between them.

C) GF modulation assessed by the slopes of the GF-LF regression lines.

D) Time lags between GF and LF (positive values indicate lagging of GF with respect to LF)

Summary

Within the present paper, we reviewed the results of several of our recent studies aimed to explore the important mechanical and neural factors affecting the GF-LF coordination. All reported findings could be of profound importance for designing, as well as for

interpreting and comparing the results of different studies of manipulation tasks. Taking into account that the tested tasks could be of importance for development of future standard quantitative tests of hand function, the presented material could also be of importance for standardizing their procedures.

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Short-Term High Intensity Plyometric Training Program Improves Strength, Power and Agility in Male Soccer Players

by

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The aim of the present study was to investigate the effects of a short-term in-season plyometric training program on power, agility and knee extensor strength. Male soccer players from a third league team were assigned into an experimental and a control group. The experimental group, beside its regular soccer training sessions, performed a periodized plyometric training program for six weeks. The program included two training sessions per week, and maximal intensity unilateral and bilateral plyometric exercises (total of 40 - 100 foot contacts/session) were executed. Controls participated only in the same soccer training routine, and did not perform plyometrics. Depth vertical jump height, agility (Illinois Agility Test, T Agility Test) and maximal voluntary isometric torque in knee extensors using Multicont II dynamometer were evaluated before and after the experiment. In the experimental group small but significant improvements were found in both agility tests, while depth jump height and isometric torque increments were greater. The control group did not improve in any of the measures. Results of the study indicate that plyometric training consisting of high impact unilateral and bilateral exercises induced remarkable improvements in lower extremity power and maximal knee extensor strength, and smaller improvements in soccer-specific agility. Therefore, it is concluded that short-term plyometric training should be incorporated in the in-season preparation of lower level players to improve specific performance in soccer.

Key words: knee extensors, depth jump, dynamometer, unilateral, plyometrics.

Introduction

Plyometric training (PT) is popular among individuals involved in dynamic sports, and plyometric exercises such as jumping, hopping, skipping and bounding are executed with a goal to increase dynamic muscular performance (Impellizzeri et al., 2008; Wilson et al., 1993; Wilson et al., 1996). In these exercises muscles undergo a rapid elongation followed by an immediate shortening (stretch-shortening contraction), utilizing the elastic energy stored during the stretching phase (Cavagna, 1977).

PT has been applied in numerous studies, and there is a general consensus that it improves sport specific skills such as agility (Miller et al., 2006) and vertical jump performance, common

measures of muscle power (Markovic, 2007). In soccer rapid movements such as acceleration and deceleration of the body, changes of direction, as well as jumps are often performed and high level of dynamic muscular performance is required at all levels of training status. In investigations mostly elite soccer players were recruited to demonstrate the effects of PT on muscular performance (Chimera et al., 2004; Ronnestad et al., 2008; Sedano Campo et al., 2009), and results are often conflicting. For example in division I female soccer players 6 weeks of PT either improved (Sedano Campo et al., 2009) or did not improve (Chimera et al., 2004) vertical jump height. In a different study male professionals were trained for 7 weeks and it was found that PT

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combined with strength training improved various dynamic measures, but not vertical jump performance (Rønnestad et al., 2008). Inconsistencies in studies can be attributed to several factors, such as gender, training status, methods of testing, different types of apparatus, and differences in duration, intensity, and the types of the exercises used in the training program (Markovic, 2007).

One problem with regard to the PT studies is that many times in short-term programs either low intensity (Rubley et al., 2011) or low impact (Miller et al., 2006) exercises are performed, or intensity is not reported at all (Miller et al., 2006; Ebben et al., 2010). In a study by Chimera et al. (2004) plyometric exercises with 30s duration or with 30 to 70 repetitions were performed continuously with a possibility of improperly inducing high fatigue in participants. Furthermore, mostly bilateral (two-leg) exercises were performed (Impellizzeri et al., 2008; Sedano Campo et al., 2009; Perez-Gomez et al., 2008; Chelly et al., 2010; Thomas et al., 2009), while including more intensive unilateral (single-leg jump) exercises into short-term PT programs may be beneficial with a goal of rapid strength gain. Makaruk et al. (2011) for example demonstrated that in untrained women unilateral jump training improved power and vertical jump height in a shorter period, compared with bilateral jump training. Though unilateral exercises have been extensively used by track and field athletes for decades in various age groups and levels to maximize sprint speed, jumping height and distance, and has also been used among recreationally trained participants in scientific investigation (Malisoux et al., 2006), there is a lack of evidence that these exercises are used in lower level soccer players. Much less information is available on the effectiveness of PT in these individuals (Thomas et al., 2009), while improving dynamic muscular performance is also highly recommended for lower class teams to focus on. Finally, single-leg plyometric movements into lateral directions are rarely included in programs, or if included, maximum intensity was not required or at least was not reported by the authors (Miller et al., 2006).

The aim of the present study was to investigate the effects of a six-week-long periodized PT program on agility and power

among male adult soccer players, using high impact unilateral and bilateral plyometric exercises. As knee extensors are highly involved in soccer movements (kicking, jumping, changes of direction), it was also our purpose to observe maximum strength changes in the knee extensor muscles. Therefore, we tested the hypothesis that the six-week-long PT program improves agility, depth vertical jump height and knee extensor strength.

Material and Methods

Participants

Twenty-four males were recruited and randomly assigned to a plyometric training (PL, $n = 12$) (age = 21.9 ± 1.7 years; body mass = 75.9 ± 2.7 kg; body height = 180.1 ± 4.0 cm) or control ($n = 12$) group (age = 22.7 ± 1.4 years; body mass = 78.6 ± 3.1 kg; body height = 180.6 ± 3.7 cm). Participants were selected from two Hungarian third league soccer teams, and have been training for at least 7 years. During the experiment participants from both groups were involved in 3 to 4 regular soccer training sessions per week, and participated in one game on the weekends. All participants have previously done unilateral or bilateral plyometric exercises. Before any training and testing an oral explanation of the experimental procedures was given to all participants. After this a written informed consent form was signed according to the Declaration of Helsinki and subjects agreed to participate in the experiment which was approved by the University Ethics Committee. All participants were familiarized with the test exercises at least one week before the beginning of the experiment. None of the participants reported current injuries of the spine or the lower extremities and no injuries occurred during the experiment.

Procedures

The experiment consisted of two test sessions (pre and post-exercise test) and a PT intervention. Pre-exercise tests were performed three days before the beginning of training and included both laboratory and field tests to evaluate lower extremity strength, power and agility. A six-week-long periodized PT program was applied, followed by post-exercise tests, three days after the last training session. During the experiment all participants continued their regular soccer training routine, that was identical

for every participant, except that group PL participated in additional PT program, and controls did the exercise tests only. All testing sessions began with a standardized warm-up: five minutes aerobic warm up (jogging) followed by stretching of the lower extremity muscles. One familiarization trial of each of the exercise tests was executed with submaximal intensity before the actual measurement. For training the participants warmed up with their usual routine. This comprised ten minutes jogging, stretching, performing 8 to 10 running drills into different directions, and 4 to 6 submaximal running strides. The plyometric drills in the experimental group were always executed immediately after the warm-up, before any other training tasks were performed on the given day.

Agility

It has been previously suggested that PT improves sport specific agility in sports where sudden movements (accelerations, stops and direction changes) are required (Yap and Brown, 2000). Two specific agility tests were performed in the present investigation. The T agility test (TAT) was applied to measure agility during direction changes such as forward sprints, left and right shuffles, and backpedalling (Miller et al., 2006). In this test three cones were set five meters apart on a straight line and a fourth cone was placed ten meters from the middle cone, forming a T shape. The Illinois agility test (IAT) was used to measure agility during sprints including direction changes without stopping, and running at different angles (Miller et al., 2006). Additional information about these tests has been reported by Miller et al. (2006). Participants performed two trials of each of the agility tests with five minutes recovery between trials, and ten minutes recovery between test types. The best time of the two trials was considered for later analysis. Times to complete the agility tests were measured every time by the same three assisting people using a stop watch. The average of the times measured by the three assistants was used for statistics. Until the end of the experiment the experimental status of the participants (PL or control) was unknown for all assistants.

Depth vertical jump performance

Depth vertical jump height (DVJ) was measured to evaluate multi-joint power

generating ability in the lower extremities. Participants were standing next to a wall extending one arm to touch the highest point possible while remaining flat-footed, to record standing reach height. After this procedure participants dropped from a 22cm platform and performed a maximal effort double-leg vertical jump using arm swing. The test was performed using the chalk method (Twist and Eston, 2005) by rubbing chalk on the fingers of the dominant hand and reaching to leave a mark on the wall as high as possible (while remaining flat-footed), after which followed a proper form to jump and place a chalk mark as high as possible on the wall. Instructions were given to quickly reverse the downward movement of the body to an upward movement in order to minimize the contact time with ground upon landing, and maximize take-off velocity. The difference between standing reach height and vertical jump height was calculated for every trial. Three trials were allowed and the best DVJ was recorded for further analysis. There was one minute rest between trials.

Maximal voluntary isometric torque

A custom-built computerized isokinetic dynamometer (Multicont II, Mediagnost, Budapest and Mechatronic Ltd., Szeged, Hungary), described in detail previously (Vácz et al., 2011), was used for the evaluation of knee extensor static strength. Participants were seated in the dynamometer's seat. The torso was stabilized with shoulder harnesses and both thighs were secured with rubberized Velcro straps to the dynamometer's seat. The shin of the dominant lower extremity, above the ankle, was fastened with a strap to the lever of a servo motor (MA-10, maximal velocity: 6000 rpm). The apparent knee joint centre of rotation was aligned with the centre of rotation of the lever arm. Participants performed three trials of maximal isometric contraction at 60° of knee angle position. It was required to slowly generate the highest possible torque with the knee extensors. From torque-time maximal voluntary isometric torque (MVC) was determined. Knee extensor torque was assessed only in the dominant (kicking) leg.

Plyometric training

Specific details of the PT program are presented in Table 1. A six-week-long training program was applied in group PL with similar

periodization described previously by Miller et al. (2006). The first two weeks (W1 and W2) were a preparatory phase, followed by three more weeks (W3-W5) with increased volume, and one week (W6) with decreased volume to taper. Training sessions were performed twice a week (Tuesdays and Thursdays) as recommended by others to allow time for regeneration (Adams et al., 1992). Unlike in other plyometric training routines the specificity of the present program was that beside double-leg jumps, high intensity single-leg exercises into both sagittal and lateral directions were also included, with a goal of rapid gain in

agility. Participants were instructed to minimize ground contact and to maximize jumping height (in hurdle, cone and depth jumps) or distance (in forward hops). It has been previously suggested that time between eccentric and concentric actions (coupling time) must be as short as possible as the shorter the coupling time, the greater the release of stored energy (Komi, 1984). A conditioning specialist supervised every training session to maximize safety by instructing proper technique and to motivate participants for maximal effort.

Table 1
A detailed description, including number of sets (first) and repetitions (second), of the six-week-long combined single and double-leg plyometric training program

	W1 to W2		W3 to W5		W6	
	Mon	Thu	Mon	Thu	Mon	Thu
<i>Plyometric exercise</i>						
Double-leg hurdle jump (90cm)	4x5	-	6x5	-	3x5	-
Single-leg lateral cone jump (35cm)	3x10	-	4x10	-	2x10	-
Single leg forward hop	3x5	-	4x5	-	2x5	-
Double-leg depth jump (55cm)	-	4x5	-	6x5	-	2x5
Double-leg lateral cone jump (35cm)	-	4x5	-	6x5	-	2x5
Single-leg hurdle jump (35cm)	-	3x10	-	4x10	-	2x10
<i>Total unilateral foot contacts/leg/session</i>	45	30	60	40	30	20
<i>Total bilateral foot contacts/session</i>	20	40	30	60	15	20

W = week

Analyses

Means and standard deviations as descriptive statistics were calculated for the measured variables. All variables were tested for normality. To identify a significant group by time interactions, 2x2 (group by time) analyses of variance with repeated measures were used for each dependent variable. When significant interaction was found Tukey's post hoc analysis was performed for pairwise comparisons. The statistical significance was set at $p < 0.05$.

Results

All variables were normally distributed as suggested by the Kolmogorov-Smirnov test

results ($p > 0.05$). The effect size for the selected variables ranged between 0.42 and 0.90. ANOVA revealed significant group by time interaction effects for TAT ($F_{1,22} = 8.49$, $p < 0.01$), IAT ($F_{1,22} = 5.09$, $p < 0.05$), DVJ ($F_{1,22} = 16.8$, $p < 0.01$), and MVC ($F_{1,8} = 11.2$, $p < 0.01$). Pre- to post-training changes for the two groups are presented in Table 2. In the PL group post-hoc tests revealed the greatest improvement in DVJ (9%) ($p < 0.05$), and MVC increased (7%) from pre- to post-training ($p < 0.05$). Small but significant improvement was found in TAT and IAT (2.5% and 1.7%, respectively) ($p < 0.05$). In controls there was no change over time in any of the measured variables.

Table 2
*Effects of the six-week-long maximal intensity plyometric training program on agility, depth vertical jump performance, and maximal voluntary torque (MVC) of the knee extensors. *Significant difference between pre- and post-test after Tukey post-hoc analysis ($p < 0.05$)*

Performance Variables	Plyometric (n = 12)					Control (n = 12)			
	Pre-test		Post-test			Pre-test		Post-test	
	Mean	SD	Mean	SD		Mean	SD	Mean	SD
T-Sprint Test (s)	11.72	0.90	11.43	0.67	*	11.87	0.43	11.98	0.41
Illinois Agility Test (s)	15.34	0.36	15.08	0.36	*	15.83	0.94	15.62	0.73
Depth vertical jump (cm)	44.8	9.5	48.8	11.1	*	40.62	4.6	40.55	7.1
MVC (Nm)	304.97	65.1	327.99	69.7	*	282.10	41.81	287.13	47.0

Discussion

In the present investigation we hypothesized that six weeks of plyometric training, comprising both unilateral and bilateral maximal intensity exercises, would produce improvements in power, strength, and agility in third league male soccer players. It was found that the training program significantly improved depth vertical jump performance, agility, and isometric knee extensor strength.

Depth vertical jump performance

The greatest improvement in the experimental group was found in depth vertical jump performance. A change of 9% indicates that significant adaptation in leg power has occurred, showing the benefits of maximal intensity PT training. The majority of the studies demonstrate positive changes in countermovement jump tests, but less data is available on depth jump performance, a more specific measure of leg power in sports, where high impact forces are present during movements. Chimera et al. (2004) reported 4% improvement in depth jump performance among athletes, while Young et al. (2009) found 7-9% improvement in non-athletes, after six weeks of PT. Considering our participants' competitive training status we conclude that 9% change in depth jump performance is remarkable, and greater

improvement has been previously noticed only in non-athletes, and after longer (8 and 15 weeks) training periods (Lehance et al., 2005; Kyrolainen et al., 2005). Such change in only six weeks in our study strengthens previous evidence that unilateral plyometric exercises can improve vertical jump performance in a short period of time (Makaruk et al., 2011). As previously suggested, positive changes in power, after such a short training period as in the present study, can be associated with the neural components of adaptation: specifically with an increased neural drive to the agonist muscles and changes in the muscle activation strategies (i.e. improved intermuscular coordination), or changes in the mechanical characteristics of the muscle-tendon complex (Markovic and Mikulic, 2010). These neurophysiological changes together may improve the ability to store and release elastic energy during the stretch-shortening cycle. Specifically, upon landing after a depth jump, an increased level of pre-activation enables the muscle sarcomeres to maintain their length, while the tendons keep elongating and store elastic energy (Kopper et al., 2012). In other words, in the eccentric phase of the depth jump the whole muscle lengthens, but the contractile apparatus maintains its length due to high activation.

Agility

When sprint performance was evaluated

after PT, results from different studies were contradicting. In male professional soccer players, Ronnestad et al. (2008) found improvements in acceleration, peak running velocity and overall sprint time (40m sprint) after 7 weeks combined PT and strength training. In contrast, Perez-Gomez et al. (2008) found no change in either short (5-30m) or long (300m) sprints after 6 weeks of a similar training program in physical education students. Similarly, Impellizzeri et al. (2008) demonstrated no effect of 4 weeks PT on 10 or 20m sprint time in amateur soccer players, probably because of the short training period.

Measuring agility could be more specific in the evaluation of the physical status of soccer players, as acceleration and deceleration, sudden stops and direction changes occur frequently during games. In the present investigation, two types of tests were applied to evaluate changes in agility. Slight but significant improvements were observed both in the T agility (2.5%) and in the Illinois agility (1.7%) tests. Fewer studies examined the effects of PT on specific agility, but results are more consistent in contrast with those obtained from sprint tests. Thomas et al. (2009) found that despite that sprint time was unchanged, six weeks of PT significantly improved agility (9%) in semiprofessional adolescent soccer players. The greatest improvement in agility (10%) was found in children soccer players after 8 weeks of PT (Meylan and Malatesta, 2009). Miller et al. (2006) found 5 and 3% improvements in the T agility and Illinois agility tests, respectively, after 6 weeks of PT. These improvements are greater than those obtained in the present study, however, making a comparison is difficult as training status of the participants is not reported in the study by Miller et al. (2006). From these research data, in agreement with our results, a conclusion can be made that a short-term PT program is effective for improving soccer specific agility, though previous studies show that sprint performance is not always enhanced in such a short interval. The magnitude of improvement in agility, on one hand, may be influenced by the training status or age of the participants, demonstrating greater agility enhancement in younger individuals versus adults. Another influencing factor can be the type of the agility test, specifically the time to complete the test. Meylan and Malatesta (2009)

used a 10m test with four 60-degree turns around a pole, and participants completed the test in an average of 4.5 seconds. Thomas et al. (2009) used the 505 agility test (Ellis et al., 2000) and the average time to complete this test for the participants was also small (2.7 seconds). Both in the study by Miller et al. (2006) and in ours the magnitude of changes in the two agility tests was smaller than in those mentioned previously. It is possible that these short term PT programs, despite that significant changes are noticed in power, show less improvement in anaerobic capacity, or muscle efficiency, the ability to maintain high mechanical work with less metabolic costs. Considering that the T agility and Illinois agility tests required ~11 and ~14 seconds to complete, respectively, during these tests not only the ATP-PC system, but the glycolytic energy system is also utilized, and this could be the explanation why improvements are smaller compared with the agility tests that require less time for execution.

Overall, improvements in agility after plyometric training can be attributed to neural adaptation, specifically to increased intermuscular coordination. Previous research also demonstrated increased proprioception after plyometric training (Myer et al., 2006). In our training protocol we also applied single leg jumps in lateral directions with the goal to increase joint stability and proprioception, important factors in performance when agility tasks are performed with stops and direction changes. Though, even with these laterally performed jump drills, improvements were less in our experiment than in others', the ~0.30 second absolute change is remarkable in only six weeks in these third league soccer players.

Knee extensor strength

Effects of PT on lower extremity strength have been characterized in various populations, and in a recent meta-analysis a conclusion was made that PT improved one repetition maximum measured in isometric or slow velocity contractions in leg muscles (Sáez-Sáez de Villarreal et al., 2010). Arazi and Asadi (2011) reported 15% gain in leg press in semi-professional male basketball players, following 8 weeks PT. Though, it has been suggested that leg muscle strength is an important factor in kicking performance (De Profte et al., 1988), limited data

are available on the effects of PT on knee extensor strength in soccer players. Maximal isometric knee extensor strength improved 7% in our participants after a program in which only explosive, and no heavy resistance training exercises were used. Similar change was found by Perez-Gomez et al. (2008) after 6 weeks training, but both plyometric and weight lifting exercises were used. Ronnestad et al. (2008) demonstrated 25% gain in 1RM squat in male Norwegian first league soccer players after 7 weeks of training, but in the program strength and plyometric exercises were combined, therefore their results are not surprising. A suggestion has been made previously that subjects in either good or poor physical condition, benefit equally from plyometric work (Sáez-Sáez de Villarreal et al., 2010). Also training volume of less than 10 weeks and with more than 15 sessions, as well as the inclusion of high-intensity programs, with more than 40 jumps per session, were the strategies that seem to maximize the probability to obtain significantly greater improvements in leg muscle strength (Sáez-Sáez de Villarreal et al., 2010). Knee extensor strength improvement in our subjects suggests increased motor unit synchronization. Measuring maximal isometric torque evaluates neuromuscular adaptation regardless of motor unit and fiber type involvement. It is possible that our plyometric training program selectively trained the fast twitch fibers and this contributed to a 7% increase in MVC, which is a measure of static contractility of all fibers. Magnitude of strength changes could also be influenced by the duration of the training program. Notably, one cannot exclude that longer programs do not increase muscle size, since plyometric training alone has been proved to induce significant hypertrophy (Malisoux et al., 2006), and if combined with resistance training it is possible that strength changes are greater (Ronnestad et al., 2008).

Discrepancies in the outcomes of the PT programs could be explained with the differences in the training intensity, volume, and whether PT was combined with strength training or not. In contrast to other studies that also used heavy resistance exercises (Ronnestad et al., 2008; Perez-Gomez et al., 2008), in the present training protocol only maximal intensity explosive exercises were utilized with an objective to

achieve a complex improvement in physical performance required for soccer, such as jumping ability, knee extensor strength and agility. We demonstrated that plyometric training alone is sufficient to increase physical performance required in soccer. One unique characteristics of the present training program is that training volume was relatively low compared with those in other studies (Miller et al., 2006; Chimera et al., 2004; Sedano Campo et al., 2009). With as short as 10 to 20 minutes training duration, and with an average of 70 foot contacts per session our participants achieved similar gains in jumping performance than that described by Seadano Campo et al. (2009) using an average of 90 foot contacts. Miller et al. (2006) applied an average of 120 contacts per session, and this increased agility more than in our protocol. Though training status of Miller' participants was not reported, based on their agility test times we assume that our participants were in better physical condition, therefore improvements are difficult to compare. Furthermore, despite that an extreme PT program with approximately 270-640 foot contacts/session were performed for six weeks, less improvement (5.8%) was reported in vertical jump height (Chimera et al., 2004), compared with our results.

Another unique characteristics of the training described in the present study is that maximal intensity unilateral exercises were also included, and they were also performed into lateral directions. These high impact jumping and hopping exercises seem to have a significant, short-term effect on depth vertical jump performance (9%) and maximal knee extensor strength (7%). It is still interesting that despite such remarkable improvement in depth vertical jump and knee extensor strength, gains in agility were relatively small, and it is possible that a combination of sprint and PT would better enhance agility. It is also possible that optimal volume, training frequency and duration would be different for improving particular performance measures in soccer (jumping ability, sprint time, agility, strength). Furthermore, using agility tests that require less time to complete, greater improvements could be noticed.

Power, strength, and agility are important performance factors in sports where dynamic movements, such as jumps, sprints, stops, direction changes, and lateral movements are

performed. Individual quality of these factors highly contributes to team performance on the field. It has been shown that elite soccer teams benefit from plyometric training, however attention must also be paid to lower class players. In European countries the number of teams in the national first league is 10 to 20, while in lower leagues this number can be manifold greater, and improving soccer specific performance is challenging for these teams. Though these teams execute much less training sessions per week when compared with professionals, such low volume and high intensity conditioning programs, with only 10 to 20 minutes duration, can fit into their training regimen. Results of the

present study indicate that 6 weeks of plyometric training consisting of maximal intensity unilateral and bilateral exercises induced remarkable improvements in lower extremity power and maximal knee extensor strength, and smaller improvements in soccer-specific agility in third league male soccer players, and these performance measures are all important factors of improving the quality of soccer games. In agreement with other authors examining elite soccer players, it is considered to be important to include short-term plyometric programs in in-season preparation in order to improve complex soccer specific dynamic performance.

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Effect of Yellow-Tinted Lenses on Visual Attributes Related to Sports Activities

by

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The purpose of this study was to clarify the effect of colored lenses on visual attributes related to sports activities. The subjects were 24 students (11 females, 13 males; average age 21.0 ±1.2 years) attending a sports university. Lenses of 5 colors were used: colorless, light yellow, dark yellow, light gray, and dark gray. For each lens, measurements were performed in a fixed order: contrast sensitivity, dynamic visual acuity, depth perception, hand-eye coordination and visual acuity and low-contrast visual acuity. The conditions for the measurements of visual acuity and low-contrast visual acuity were in the order of Evening, Evening+Glare, Day, and Day+Glare. There were no significant differences among lenses in dynamic visual acuity and depth perception. For hand-eye coordination, time was significantly shorter with colorless than dark gray lenses. Contrast sensitivity was significantly higher with colorless, light yellow, and light gray lenses than with dark yellow and dark gray lenses. The low-contrast visual acuity test in the Day+Glare condition showed no significant difference among the lenses. In the Evening condition, low-contrast visual acuity was significantly higher with colorless and light yellow lenses than with dark gray lenses, and in the Evening+Glare condition, low-contrast visual acuity was significantly higher with colorless lenses than with the other colors except light yellow. Under early evening conditions and during sports activities, light yellow lenses do not appear to have an adverse effect on visual attributes.

Key words: sports, low-contrast visual acuity, contrast sensitivity, dynamic visual acuity.

Introduction

The visual attributes of athletes have attracted attention from researchers in sports science and sports medicine (Stine et al., 1982; Christenson and Winkelstein, 1988; Zwierko, 2007; Zwierko et al., 2010). According to previous reports, athletes tend to have better visual attributes than non-athletes, and competitive athletes tend to have better visual attributes than other athletes. Therefore, visual attributes are important factors for those who participate in sports activities. Typical visual attributes involved in sports activities include: dynamic visual acuity, which is the ability to recognize a moving target; depth perception, which is related to a sense of distance; hand-eye coordination; contrast

sensitivity; and low-contrast visual acuity (Hoffman et al., 1984; Hitzeman and Beckerman, 1993; Erickson et al., 2009; Laby et al., 2011).

In general, athletes protect their eyes from ultraviolet rays by wearing sunglasses (Miller, 1974; Fishman, 1986; Cooper et al., 2001). Several previous reports have investigated eye diseases and disorders related to ultraviolet rays and blue light rays which have a short wavelength along the visible light spectrum (Ham et al., 1976; Taylor et al., 1988; Zigman, 1992; McCarty and Taylor, 2002). Lawler et al. (2007) investigated the use of sunglasses by field hockey, soccer, and tennis players. The lens color of conventional sunglasses is usually black, but blackening and darkening athletes' vision may negatively affect performance

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in some sports. Therefore, it is difficult to say that black lenses with low luminous transmittance are suitable for all sports. Currently, lenses of various colors and luminous transmittances are available, but it may be difficult for athletes and other consumers to choose the proper lens for certain occasions.

Yellow lenses are one example of a novel type of lens that is currently attracting attention. The color yellow cuts blue light rays, and it gives a high luminous transmittance around a wavelength of 550 nm, to which the human eye is very sensitive. Several authors have already studied the effect of yellow lenses on aspects of visual performance such as contrast sensitivity (Kelly et al., 1984; Yap, 1984; Rieger, 1992; Leguire et al., 1993; Provines et al., 1997; Wolffsohn et al., 2000). However, opinions on this effect are divided, and few of the previous studies selected appropriate measurement items and subjects for sports activities. Moreover, it is likely that product-development research on color lenses examines only the wearer's comfort rather than the impact of the lenses on visual attributes. It would be very interesting to clarify the effect of yellow lenses on visual performance, which is considered to be an important factor for athletes. It is also necessary to study the effect under various conditions, such as a dim environment or the presence of a glaring light source.

Taking into account various conditions encountered during sports activities, the present study aimed to clarify the effect of various types of color lenses on visual attributes. It is anticipated that effects of lenses color on visual attributes vary among lenses because luminous transmittance differ among color lenses. The results are expected to be of help in developing new color lenses for athletes and in assisting other types of consumers to choose an appropriate color lens.

Material and Methods

The subjects were 24 students (11 females, 13 males) at a sport-oriented university. Their average age was 21.0 ± 1.2 years. Subjects whose decimal visual acuity, unaided or with contact lenses, was greater than 1.0 (logMAR 0.0) were included; 14 used contact lenses and 10 were unaided. All subjects had sports experience such as Squash, Basketball, Volleyball, Track and field,

baseball, tennis, and so on. Contrast sensitivity, dynamic visual acuity, depth perception, and hand-eye coordination were measured with binocular vision. Visual acuity and low-contrast visual acuity were measured with the dominant eye, which was the left eye in 11 subjects and the right eye in 13. The dominant eye was determined by pointing to an object with the index finger or placing the object in a circle made with the hands.

The subjects provided their written, informed consent before participating in the experiment. This study was approved by the Research Ethics Committee of the Juntendo University Graduate School of Health and Sports Science.

Lenses of 5 colors were used: C, LY, DY, LG, and DG. Figure 1 shows the luminous transmittance of each lens. The five colors of lenses used in this experiment were: colorless (C; luminous transmittance 92.0%), light yellow (LY; luminous transmittance 65.2%), dark yellow (DY; luminous transmittance 30.4%), light gray (LG; luminous transmittance 65.9%), and dark gray (DG; luminous transmittance 30.2%).

Measurement Procedure

Before measuring, each experimental lens (experimental spectacles) was fitted by an optician for each subject. Lenses of each color were used in random order. For each lens condition, measurements were performed in a fixed order: contrast sensitivity, dynamic visual acuity, depth perception, hand-eye coordination and visual acuity and low-contrast visual acuity. These measurements for each lens were considered a set, and an interval of >15 min was taken between sets. The measurement method is outlined below. A questionnaire was also administered at the end of the experiment.

1. *Visual acuity and low-contrast visual acuity.* Visual acuity and low-contrast visual acuity were measured using a contrast sensitivity acuity tester (CAT-CP, NEITZ Co., Ltd., Tokyo, Japan) (Lee et al., 2001). The subject looked into the tester and attempted to determine the direction of the gap in a Landolt ring. Measurement was performed automatically. The conditions for the measurement were in the order of Evening, Evening+Glare, Day, and Day+Glare. The luminances of the visual target were 200 cd/m² in the Day condition and 10 cd/m² in the Evening condition. The illuminance of Glare with

light-emitting diode (LED) light was 200 lx. Under each condition, a visual acuity test (contrast 100%) and low-contrast visual acuity tests (contrast 10% and 5%) were performed. Measurements were performed with the dominant eye in the order of visual acuity, low-contrast visual acuity of 10%, and low-contrast visual acuity of 5%. The visual acuity and low-contrast visual acuity were measured by logMAR values. In the 5% and 10% contrast conditions, if the subject could not determine the gap even for the lowest value of the tester (log MAR 1.3), the data were processed as logMAR 1.4.

2. *Contrast sensitivity.* Contrast sensitivity is ability to distinguish between dark and light. Contrast sensitivity was measured using a Sine Wave Contrast Test (Stereo Optical Co., Inc., Chicago, IL, USA) (Kohmura et al., 2008; Furuta et al., 2009), and contrast sensitivity was measured at each spatial frequency of 1.5, 3, 6, 12, and 18 cycles/degree. Each of the circles in the cart contains lines. The subject attempted to determine the direction of the line (left, right or up). The distance between the subject and the chart was 3.0 m.

Figure 1

Visible light transmission of the lenses used in this experiment is shown.

The luminous transmittance value is 92.0% for colorless lenses, 65.2% for light yellow lenses, 30.4% for dark yellow lenses, 65.9% for light gray lenses, and 30.2% for dark gray lenses

Figure 2

Device for measuring hand-eye coordination.

3. *Dynamic visual acuity.* Dynamic visual acuity was measured using a dynamic visual acuity test apparatus (HI-10, Kowa Co., Ltd., Aichi, Japan) (Kohmura et al., 2008). In this test, the subject attempted to determine the direction of the gap in a Landolt ring moving from left to right on a semi-circular screen. The rotational speed of the Landolt ring gradually decreased from 49.5 rpm. The subject pressed the switch as soon as he or she determined the direction of the gap in the Landolt ring, and immediately gave an answer. If the answer was correct, the rotational speed when the subject pressed the switch was recorded. The size of the Landolt ring was equivalent to the decimal visual acuity 0.025 (logMAR: 1.6). The Landolt ring was projected by a slide projector onto a 120 cm semicircular screen. The screen was located 80 cm away from the subject. The luminance of this visual target was about 1300 cd/m². The direction of the gap of the Landolt ring could be up, down, left, or right, and it was presented in random order. The measurement was repeated until five records were obtained, and the average of the records was considered the measured value. If the subject made three or more mistakes, the test was re-started.

4. *Depth perception.* Depth perception was measured using a depth perception test apparatus (AS-7JS1, Kowa Co., Ltd.) (Kohmura et al., 2008; Furuta et al., 2009). The apparatus contained three bars, and the central bar moved back and forth at a speed of 50 mm/s. The other two bars on the sides were fixed. Subjects were able to see the bars from a window in the device. The subject attempted to press a switch to stop the central bar when he or she felt that the three bars were laterally positioned in line with each other. After two practice runs, three measurements were performed. The absolute value of the displacement between the central bar and the other two bars was recorded. This displacement was measured in millimeters. The distance between the subject and the apparatus was 2.5 m.

5. *Hand-eye coordination.* Hand-eye coordination was measured using the AS-24 (Kowa Co., Ltd.) (Wada et al., 2007; Uematsu et al., 2009) (Figure 2). The test apparatus had 120 lamps on its panel, and the lamps were lit one at a time in random order. After a lamp was lit, the next lamp was lit 1.3 sec later, or immediately if the subject pushed the lamp. The subject attempted to push the

lamps as accurately and quickly as possible, and the time (seconds) taken to light the 120 lamps was recorded. One measurement was performed for each lens.

6. *Questionnaire.* Using visual analog scales, each question was answered by marking on a 100-mm line (the length in millimeters was not written on the questionnaire sheet) on the basis of a subjective assessment and impression. The questionnaire was conducted after all the visual attribute measurements were finished. The positions of the marks made by the subjects were measured in millimeters. Subjects were asked to evaluate the following five qualities: brightness (Bright: 100 mm, Dark: 0 mm), sharpness (Sharp: 100, Blurry: 0), changes in color recognition (Not changed: 100, Changed: 0), glare (when looking at a fluorescent light in the room) (No glare: 100, Glare: 0), and overall impression (Good: 100, Bad: 0).

Statistical Processing. Two-way repeated measures analysis of variance (ANOVA) with factors of contrast and lens was used for contrast sensitivity and low-contrast visual acuity. One-way repeated measures ANOVA was used for dynamic visual acuity, depth perception, hand-eye coordination, visual acuity, and the questionnaire. The significance level was set at $p < 0.05$.

Results

Measurement Results of Visual Attributes are presented in Table 1.

For low-contrast visual acuity, in every condition, the interaction was not significant and the main effect of contrast was significant at $p < 0.01$ (Day: $F=98.10$, $p=0.00$, Day+Glare: $F=215.55$, $p=0.00$, Evening: $F=199.63$, $p=0.00$, Evening+Glare: $F=160.73$, $p=0.00$).

In the Day condition, the main effect of lens was significant at $p < 0.05$ ($F=2.68$, $p=0.04$), and multiple comparisons showed a significant difference between C and DG at $p < 0.05$ ($p=0.04$). In the Day+Glare condition, there was no significant difference. In the Evening condition, the main effect of lens was significant at $p < 0.01$ ($F=4.80$, $p=0.00$), and C and LY had significant differences from DG at $p < 0.01$ (C vs. DG: $p=0.00$, LY vs. DG: $p=0.01$). Finally, in the Evening+Glare condition, the main effect of lens was significant at $p < 0.01$ ($F=5.37$, $p=0.00$), and C had significant

differences from DY ($p=0.02$), LG ($p=0.01$), and DG ($p=0.00$).

For contrast sensitivity, the interaction was not significant, and the main effects of lens and contrast were significant at $p<0.01$ (lens: $F=10.54$, $p=0.00$, contrast: $F=178.34$, $p=0.00$).

DY and DG had significant differences from C, LY, and LG. C vs. DY ($p=0.01$), LY vs. DY ($p=0.00$), LG vs. DY ($p=0.00$), and LG vs. DG ($p=0.00$) were significant at $p<0.01$. C vs. DG ($p=0.01$) and LY vs. DG ($p=0.02$) were significant at $p<0.05$.

For dynamic visual acuity and depth perception, there were no significant differences. For hand-eye coordination, the result of ANOVA was significant at $p<0.05$ ($F=3.48$, $p=0.01$), and the result of the multiple comparisons showed a significant difference between C and DG at $p<0.05$ ($p=0.05$).

For visual acuity, there were no significant differences in the Day, Day+Glare, and Evening conditions. However, in the Evening+Glare condition, the result of ANOVA was significant at $p<0.05$ ($F=3.48$, $p=0.01$).

Questionnaire results are presented in Table 2.

For all items included in the questionnaire, the result of one-way ANOVA was significant at

$p<0.01$ (brightness: $F=27.34$, $p=0.00$, sharpness: $F=9.63$, $p=0.00$, color: $F=71.15$, $p=0.00$, glare: $F=7.90$, $p=0.00$, overall: $F=16.14$, $p=0.00$). The results of the multiple comparisons were as follows: regarding the question about brightness, C presented significant differences from LG ($p=0.00$) and DG ($p=0.00$), LY from DY ($p=0.00$), LG ($p=0.00$), and DG ($p=0.00$), DY from DG ($p=0.00$), and LG from DG ($p=0.00$); as far as sharpness was concerned, C was significantly different from DY ($p=0.01$), LG ($p=0.03$), and DG ($p=0.01$), LY from DY ($p=0.00$) and DG ($p=0.01$), and LG from DG ($p=0.01$); for the question about changes in color recognition, every combination had a significant difference at $p<0.01$ ($p=0.00$), except for LY and DY ($p=0.01$), and LY and DG ($p=0.04$), where the significance was at $p<0.05$; for the question about glare, C showed significant differences from LG ($p=0.00$) and DG ($p=0.00$), LY from DG ($p=0.01$), and LG from DG ($p=0.04$); and with regard to the overall impression, C was significantly different from DY ($p=0.00$) and DG ($p=0.03$), LY from DY ($p=0.00$), DY from LG ($p=0.00$), and LG from DG ($p=0.00$).

Table 1
Mean and standard deviation of visual performance related to sports activities with each of the lenses.

		Dynamic visual acuity	Depth perception	Eye-hand coordination	Visual acuity (log MAR)			
		(rpm)	(mm)	(sec)	Evening	Evening +Glare	Day	Day +Glare
Colorless	M	43.4	8.4	87.7	0.07	0.06	-0.01	-0.02
	SD	3.2	5.1	7.0	0.18	0.19	0.16	0.13
Light yellow	M	42.7	9.1	88.3	0.05	0.05	-0.02	-0.05
	SD	3.8	5.6	6.2	0.20	0.17	0.14	0.09
Dark yellow	M	42.4	6.9	88.6	0.09	0.09	-0.04	-0.06
	SD	3.3	7.6	6.1	0.17	0.19	0.17	0.06
Light gray	M	43.4	8.9	88.0	0.09	0.15	-0.01	0.01
	SD	3.2	7.0	6.7	0.22	0.23	0.18	0.21
Dark gray	M	43.0	10.9	90.3	0.09	0.14	-0.03	-0.02
	SD	3.3	12.3	6.5	0.14	0.19	0.12	0.17

Table 2

Questionnaire results

Score	Brightness		Sharpness		Color		Glare		Overall	
	M	SD	M	SD	M	SD	M	SD	M	SD
Colorless	75.2	18.9	77.9	19.5	93.8	11.7	33.2	26.5	77.6	22.2
Light yellow	81.4	12.8	75.7	17.2	33.3	23.1	40.0	25.8	59.8	19.4
Dark yellow	56.8	25.7	52.2	23.6	17.7	18.1	51.1	27.7	32.7	22.3
Light gray	50.4	22.5	61.7	21.8	73.3	20.5	54.2	28.6	73.0	17.2
Dark gray	28.2	23.4	53.2	26.4	56.2	27.3	69.3	26.7	50.0	27.3

Figure 3

Measurements results for low-contrast visual acuity are shown.

In the Day condition, the statistical analysis shows a significant difference between colorless and dark gray at $p < 0.05$.

In the Day+Glare condition, there is no significant difference.

In the Evening condition, colorless and light yellow have significant differences from dark gray at $p < 0.01$.

In the Evening+Glare condition, colorless is significantly different from dark yellow ($p < 0.05$), light gray ($p < 0.01$), and dark gray ($p < 0.01$).

Figure 4

Means of contrast sensitivity with each of the lenses are shown.

Dark yellow and dark gray have significant differences from colorless, light yellow and light gray.

Colorless vs. dark yellow, light yellow vs. dark yellow, light gray vs. dark yellow, and light gray vs. dark gray are significantly different at $p < 0.01$.

Colorless vs. dark gray and light yellow vs. dark gray are significantly different at $p < 0.05$.

Discussion

There were no significant differences among the tested lenses with respect to dynamic visual acuity or depth perception. When recognizing a target in the fovea as in the dynamic visual acuity test, or determining the distances of the three bars by steadily looking at them, the effects of lens color and luminous transmittance are assumed to be minor. In such circumstances, the differences among the lenses used in this experiment appeared to be small. During sports activities, adverse effects of the lenses used in this study on the visual attributes related to tracking a ball or person with the eye or recognizing the positional relationship of a ball and a person might be small.

On the other hand, for hand-eye coordination, the time was significantly shorter for C than DG. Taking into consideration that this time is the time taken to push all the 120 lamps in this measurement, a shorter time represents a better result, where the subject could push the

lamps quickly and accurately. In repeatedly finding a lamp in the peripheral vision and pushing it accurately, DG appears to have some effects. In sports that require quick and accurate responses, using DG lenses may have some adverse effects. It is suggested that the extent of this effect could be different between situations in which the eyes are always directed to the target and those in which a response to a target in the peripheral vision is required.

Contrast sensitivity was significantly higher for C, LY, and LG than for DY and DG, and in the Day condition, low-contrast visual acuity was significantly higher for C than DG. Therefore, it is assumed that a low luminous transmittance may affect contrast-related features of the lens under normal circumstances such as daylight. However, the low-contrast visual acuity test in the Day+Glare condition showed no significant difference among the lenses. In a glare situation, such as in the presence of glare during daylight,

all lenses tested in this study appeared to have little effect on the contrast attributes. Therefore, in a bright situation during daylight, using a low luminous transmittance lens might not significantly affect visual attributes. On a sunny day, a lens with low luminous transmittance is assumed to be usable without an effect on low-contrast visual acuity. Recently, although the usage and situations were very different from the lenses used in this study, there have also been reports regarding the effect of colored contact lenses in sports activities (Porisch, 2007; Cerviño et al., 2008). Erickson et al. (2009) studied and reported the effect of colored contact lenses; they found that using amber and gray-green contact lenses with luminous transmittances of 50% and 36%, respectively, could achieve better contrast sensitivity than using colorless lenses in bright sunlight.

In contrast to the above discussed Day conditions, in the Evening condition, low-contrast visual acuity was significantly higher for C and LY than DG, and in the Evening+Glare condition, low-contrast visual acuity was significantly higher for C than for other colors except LY. Therefore, particularly under slightly dim circumstances such as early evening, LY lenses have little effect on low-contrast visual acuity and may be usable in the same manner as colorless lenses. That is to say, it is expected that even in a dim environment where a single strong light source is present, such as sunset, LY lenses can prevent injuries and make the vision brighter while maintaining the visual attributes.

For the question about brightness, C and LY were rated light, DG was rated dark, and DY and LG were considered the same. As for sharpness, C was rated sharper than any lenses other than LY. For each color, the light lenses seemed to be considered sharper than the dark lenses, and LY was rated sharper than DG. It has been previously reported that yellow lenses seem brighter (Kelly, 1990; Chung and Pease, 1999), and this could be said to be a major feature of yellow lenses.

As for changes in color recognition, C was rated to cause the least change, followed by LG, DG, LY, and DY. The subjects seemed to have felt that yellow lenses affected their color recognition, as reported in previous studies (Hovis et al., 1989; de Fez et al., 2002). Several advantages of yellow lenses have been reported, as mentioned above,

but the drawback of impaired color recognition must be taken into consideration. As for glare, DG was rated to have less glare than C, LY, and LG, and LG was rated to have less glare than C. Finally, as for the overall impression, C and LG were rated better than the dark lenses, and LY was rated better than DY.

Based on the above presented results, other than the question about glare, ratings for dark colors tended to be lower than those for the light colors. Generally speaking, people are most accustomed to using black lenses, and yellow lenses are unfamiliar because they change the wearer's color recognition. To encourage consumers to use yellow lenses, it is important to inform them of both the advantages and disadvantages. Yellow lenses can be used during sports activities in which color recognition is not critical. However, in sports where many athletes participate with various colored uniforms, changes in color recognition may have adverse effects on performance, and colored lenses must therefore be used with care. Recently, the effects of lenses of other colors that were not used in this study have also been studied (Lee et al., 2002). In the future, it will be necessary to conduct studies investigating which lenses are suited for different practical situations, including sports activities.

Dark lenses appear to have a greater effect on contrast-related features, whereas under early evening conditions, LY could be used without adverse effects on visual attributes. Under bright conditions, such as in the daylight with glare, the lenses used in this study do not appear to be significantly different in their measured effects on visual attributes.

Moreover, when tracking the position of or determining the distance of a target by looking steadily at the target, the effects of the studied lenses on visual attributes appear to be small. However, when it is necessary to locate a target in the peripheral vision and quickly and accurately respond, as in ball sports, DG may have adverse effects. Therefore, depending on the type of sport, using dark colored lenses may affect athletes' performance.

According to the subjective opinions collected through the questionnaire, LG, a light and familiar black color, appeared to be better rated than the other lenses. This may have been because the subjects were used to black lenses and

were uncomfortable with yellow lenses because they changed their color recognition and the brightness of the field of view.

The results of this experiment show that under early evening conditions and during sports activities, light yellow lenses do not appear to have an adverse effect on visual attributes. It is assumed that using yellow-tinted lenses during sports activities is one of the useful methods to protect eyes from ultraviolet rays and a blue light

without adverse effect on visual attributes. However, color lenses need to be developed further, taking into account how the color of the lens and the luminous transmittance properties affect the visual attributes and subjective feelings of the wearer. Furthermore, the subjects of this study were young, with an average age of 21 years; taking into account that visual attributes change with age, it is also important to study the effects of colored lenses on visual attributes in subjects in other age groups.

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Asymmetry of Spinal Segments Mobility in Canoeists and its Relationship with Racing Speed

by

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The aim of this study was to determine the extent of asymmetry of spinal segment mobility in canoeists. Moreover, the relationship between this parameter and racing speed was analyzed. The study included 18 canoeists with a mean age of 16.4 years. Mobility of cervical, thoracic and lumbar spine, in sagittal, coronal and transverse planes, was measured with the aid of a tensometric electrogoniometer. The racing speed was based on results achieved during the qualifying competition for the Polish national team. Spinal mobility was measured within two days after the competition. Significant associations were observed between average racing speed and the asymmetry coefficients of the cervical ($r=-0.52$; $p=0.03$) and lumbar spinal flexure in the coronal plane ($r=0.57$; $p=0.01$). The extent of the asymmetry of the cervical spine flexure in the coronal plane should possibly be reduced, because such asymmetry exerts a negative effect on racing speed. In contrast, canoeist's training should be oriented towards increasing the asymmetry of the lumbar spine flexure in the coronal plane. However, one should keep in mind that such an approach, although favorable in terms of race performance, could negatively affect the canoeist's health.

Key words: sports training, spine flexion, health, competitive canoeists.

Introduction

Achieving satisfactory sport results in kayaking requires a significant level of muscular strength (Mann and Kearney, 1980). Therefore, athletes practicing this sport need to develop sufficient strength of the upper body, including the trunk (Tesch, 1983; Fry and Morton, 1991; Fekete and Coach, 1998; Akca and Muniroglu, 2008). Canoeing is a paddling discipline that requires the athletes to paddle on one side of the boat, left or right. Such paddling technique requires an asymmetric position of the body and performance of asymmetric muscular work (Rynkiewicz and Starosta, 2011). The canoeist paddles in a step forward/backward position, kneeling on one leg. During the preparatory phase of the paddling movement an athlete performs rotation/bending of the trunk and

subsequently utilizes muscular strength of the trunk to maximally propel the canoe during the active phase of the movement. Usually, bilateral paddling is not practiced during canoeing training; therefore, such long-term specialized training can result in an asymmetric distribution of muscular mass and tone (Ilnicka, 1999; Andreoli et al., 2001; Sanchis-Moysi et al., 2004). Abnormal body gait is one possible consequence of disproportions that can even lead to an asymmetric structure of the skeleton (Cibulka et al., 1998; Tanchev et al., 2000; Sanchis-Moysi et al., 2004). Asymmetrical lifting and twisting have been linked to increased incidence of disc prolapse and low back pain (Andersson 1981; Kelsey et al., 1984). Finite element models predicted that maximum symmetric efforts produce tensile strains in the annulus fibers of 10% but when combined with bending and

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twisting the strains increase to 20% (Shirazi-Adl et al., 1986).

Additionally, injury and joint overload as well as degenerative changes have been reported in some cases as a consequence of these abnormalities (Omey et al., 2000; Tanchev et al., 2000; Kazunori et al., 2006). This is particularly dangerous in young athletes, especially during the phase of intense development of skeletal structures and muscle tissue growth.

Proper spine function, particularly the range of mobility, plays a vital role in determining one's strength. Previous studies revealed that sport training affects the functional parameters of a canoeist's spine, and disproportions of spinal mobility have been observed in canoeists depending whether they paddle on the right or left side of the boat (unpublished results of research). All the above-mentioned malfunctions may lead to numerous negative changes manifested later in life. In addition, previous studies have not revealed whether changes in spinal segment mobility influence sports results, in particular the speed achieved during canoe paddling.

The aim of this study was to reveal the effect of side (left and right) of paddling on spinal segment mobility. Additionally, we assessed whether the level of asymmetry of spinal segment mobility is associated with the speed achieved during canoe racing. We tested the hypotheses that left-paddling and right-paddling canoeists differ in terms of the degree of spinal flexure and that the paddling speed is correlated directly with the level of asymmetry in spinal segment mobility.

Material and Methods

Participants

The study included 18 advanced canoeists with a mean age of 16.4 years ($\pm$ SD). Ten athletes were left-sided paddlers and the remaining eight were right-sided. The participants of our study had a very high level of athletic abilities, confirmed by the fact that five of them qualified for the national junior team.

Procedures

The racing speed, km/h, of the canoeist-canoe system (V) was based on a competition, where Olympic distances were used, held for qualifications to the junior national team. This

competition took place two days before spinal segment mobility was measured. Spinal mobility was determined by the electrogoniometric method using a Penny & Giles electrogoniometer (Biometrics Ltd, Gwent, UK) that took measured angular movements in individual spinal articulations (Troke and Moore, 1995; Thoumie et al., 1998; Christensen, 1999; Lewandowski, 2006). This method is characterized by high reliability and precision, and the obtained results are comparable to those determined radiologically and to Polish population normative values (Lewandowski, 2006).

The measurements were taken in cervical, thoracic and lumbar spinal segments. Spinal mobility was determined in coronal, sagittal, and transverse planes, and the respective asymmetry coefficients were calculated based on the following formula (Siniarska and Sarna, 1980):

$$A = \frac{X_p - X_l}{\frac{(X_p + X_l)}{2}} \cdot 100 \%$$

A – asymmetry coefficient;

X_p – the value of a given characteristic determined on the right side;

X_l – the value of a given characteristic determined on the left side.

Direct values of asymmetry coefficients (A_m) were calculated for the mobility of individual spinal segments, and coefficients of correlation were calculated between those parameters and the paddling speed. This method enabled us to analyze the potential associations between the degree of asymmetry and the racing speed, irrespective of the side of the boat chosen by the canoeists for paddling.

All the procedures of this study were approved by the Local Ethics Committee by the Karol Marcinkowski University of Medical Sciences in Poznan, Poland.

Analysis

All calculations were carried out using the Statistica 9.0 package (StatSoft, Inc. 1984, 2011, license no. AXAP012D837210AR-7). The results were presented as arithmetic means (M), $\pm$ standard deviations ($\pm$ SD), and the normality of their distributions was verified. Mean values of analyzed parameters determined in athletes paddling on the right and left side of a canoe were compared using ANOVA. Post-hoc tests were

used for detailed comparisons of parameters with normal distributions. Due to high variability in the sample size of canoeists paddling on the right or the left side, the Tukey test for unequal samples was used as a post-hoc test. The Kruskal-Wallis test was used for comparisons of variables with non-normal distribution. Additionally, Pearson's and Spearman's coefficients of correlation were calculated between the asymmetry coefficients and paddling speed. Statistical significance was defined as $p < 0.05$.

Results

No significant differences were observed between mean V of right- and left-paddling athletes (Table 1). The only observed significant difference in spinal mobility pertained to the

maximal left rotation of the cervical spine (CTL): it was lower in right-sided paddlers (RP) than in left-sided paddlers (LP), 60.38 and 67.7, respectively, for RP and LP left side of the canoe.

The asymmetry coefficients of spinal mobility were subjected to correlation analysis, separately for RP and LP (Table 1). For RP, increasing left rotation of the cervical spine was associated with higher V ($r = 0.81$; $p = 0.01$).

In the analysis that combined data for RP and LP, significant inverse correlation was observed between the asymmetry of cervical spine mobility in the coronal plane (CCoAm) and V ($r = -0.52$; $p = 0.03$), (Figure 1). Additionally, significant direct correlation was revealed between the asymmetry of lumbar spine flexure in the coronal plane (LCoAm) and V ($r = 0.59$; $p = 0.01$) (Figure 2).

Table 1
Anthropometric measurements and coefficients of asymmetry in right side (RP) and left side (LP) paddlers (n=18)

	RP n=8		LP n=10	
	M	± sd	M	± sd
V [km/h]	13,45	1,05	13,42	0,47
CSA [%]	-73,86	37,43	-73,65	24,21
CSAm [%]	75,29	34,03	73,65	24,21
CCoA [%]	-6,98	23,12	-1,69	7,45
CCoAm [%] *	17,46	15,55	5,45	5,07
CTA [%]	2,40	19,16	-7,79	18,61
CTAm [%]	26,00	6,61	31,50	11,42
ThSA [%]	-72,36	60,81	-50,79	54,39
ThSAm [%]	73,97	58,55	62,40	38,70
ThCoA [%]	-5,31	24,94	4,33	28,64
ThCoAm [%]	19,42	14,93	23,45	15,16
ThTA [%]	2,47	60,29	0,27	52,10
ThTAm [%]	51,48	24,76	41,06	28,99
LSA [%]	116,27	34,20	84,32	30,78
LSAm [%]	116,27	34,20	84,32	30,78
LCoA [%]	-5,09	41,08	1,56	29,13
LCoAm [%] *	32,47	22,63	20,75	19,30
LTA [%]	18,36	70,60	7,19	40,98
LTA _m [%]	56,49	41,52	33,43	22,24

* Significant correlation between speed and spinal mobility factor

M, mean; ± SD, standard deviations;

C, cervical spine; Th, thoracic spine; L, lumbar spine; Co, coronal plane;

S, sagittal plane; T, transverse plane;

A, asymmetry; Am direct values of asymmetry

Figure 1

Correlations between paddling speed and asymmetry of the cervical spine mobility in the coronal plane (n=18)

Figure 2

Correlations between paddling speed and asymmetry of the lumbar spine mobility in the coronal plane (n=18)

Discussion

Our study revealed that the degree of left rotation is significantly lower in RP as compared to LP. Higher degree of left rotation documented in canoeists preferring the left side could be

associated with the specificity of canoe paddling. Torsion of the body is required to achieve propulsion; during this movement the head is frequently rotated to the opposite side and kept parallel to the direction of canoe movement (Rynkiewicz and Starosta, 2011). In such cases, left

rotation of the cervical spine is observed in athletes paddling on the left side of the canoe, whereas right rotation takes place in right-sided canoeists. A lack of similar intergroup differences in the right rotation of cervical spine can result from individual characteristics of head position during paddling.

Correlation analysis revealed an interesting finding: an increase in the left rotation of cervical spine was found to be associated with a higher racing speed in RP. This correlation suggests that the degree of head rotation is similar to that of the trunk, and consequently that the head is not kept parallel to the direction of canoe movement as previously suggested. Rotating the head in the direction of canoe movement can lead to rigidity of the cervical spine, preventing its contralateral rotation and blocking the development of significant strength of the spinal extensors. Consequently, one can assume that athletes with greater left rotation paddle with

their heads positioned in the same direction as their trunks. As a consequence of long-term sports training, a higher mobility of the cervical spine is achieved and a relatively better racing speed is accomplished as compared to athletes with lesser rotation.

Furthermore, we observed that the level of asymmetry in the mobility of the cervical spine in the coronal plane was inversely correlated with racing speed. This means that an increase in the asymmetry can be reflected in lower speed (Figure 1). The level of asymmetry was higher in RP, but this difference proved insignificant due to high variability of individual results. The asymmetry observed in the cervical spine mobility in the coronal plane resulted from the asymmetry of sport technique. This negative tendency can lead to degenerative changes within the spine, having harmful health consequences (Sward, 1990; Sward et al., 1990; Cibulka et al., 1998; Omeý et al., 2000; Tanchev et al., 2000; Sanchis-Moysi et al., 2004; Kazunori et al., 2006).

Picture 1

Back view of the left side paddler in the phase of water grip

In contrast, we observed a significant positive correlation between the asymmetry of the lumbar spine flexure in the coronal plane and racing speed. Specifically, increased asymmetry was associated with a higher racing speed (Figure 2). Many years of sport's training are reflected by adaptive changes, including asymmetry of mobility of spinal segments. These types of adaptive changes are necessary to increase racing speed; however, it is still unclear whether the resulting changes affect an athlete's health negatively. Long-term training is reflected by the asymmetry in the distribution of skeletal structure (Sanchis-Moysi et al., 2004), muscle mass and its tone (Cibulka et al., 1998; Ilnicka, 1999; Andreoli et al., 2001) as well as spine mobility, potentially leading to injuries and degenerative changes (Andersson, 1981; Kelsey et al., 1984; Sward, 1990; Sward et al., 1990; Omeij et al., 2000; Kazunori et

al., 2006). Resulting changes in the spine are particularly harmful to athletes' health and can limit their normal functioning in everyday life after finishing their professional careers (Picture 1).

Conclusions

A comparison of athletes paddling on the right and left side of the canoe revealed significant differences in the degree of left rotation of the cervical spine in the transverse plane.

Increased asymmetry in the cervical spine flexure in the coronal plane negatively influences racing speed. In contrast, higher asymmetry of the lumbar spine flexure in the coronal plane was associated with higher values of paddling speed.

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Bilateral and Unilateral Asymmetries of Isokinetic Strength and Flexibility in Male Young Professional Soccer Players

by

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This study investigated bilateral and unilateral asymmetries of strength and flexibility in male young professional soccer players. Thirty-six soccer players (age: 18.9 ± 1.4 years) participated in this study. A Biodex Isokinetic Dynamometer was used to assess the hamstring and quadriceps strength at selected speeds of 60°/s, 180°/s and 300°/s. Hip joint flexibility was measured using a goniometer. No difference was observed in conventional strength ratio, dynamic control ratio and fast/slow speed ratio between the dominant and non-dominant legs ($p > 0.05$). All but one of the players (97.2%) had musculoskeletal abnormality (bilateral imbalance $> 10\%$) in one or more specific muscle groups. The dominant leg had greater hip joint flexibility compared with the non-dominant leg ($108.8 \pm 10.7^\circ$ versus $104.6 \pm 9.8^\circ$, respectively). The findings support the hypothesis that physical performance and movement pattern experienced during soccer playing may negatively change the balance of strength in both legs (bilateral strength balance), but not on the same leg of the young male professional soccer players. The results can be helpful for trainers and coaches to decide whether the players need to improve their balance and strength which in turn may prevent injury. It is suggested that in professional soccer training, quadriceps and hamstrings muscle strength, as well as hip joint flexibility should not be overlooked.

Key words: isokinetic strength, flexibility, competitive soccer players.

Introduction

Strength and flexibility are two of the key indicators of physical performance in soccer players (Lehance et al., 2009). Particularly during dynamic movements in soccer, balance in strength and flexibility between the dominant and non-dominant legs provide joint stability. Strength and flexibility asymmetries between the two limbs and reciprocal strength ratio between the agonist and antagonist muscles especially in lower body reportedly play an important role in sports with asymmetric kinetic patterns like soccer (Rahnema et al., 2005; Fousekis et al., 2010). Most soccer players favour or are forced to use one particular leg for ball kicking and cutting skill

(Fousekis et al., 2010) and this preference is the possible cause of asymmetry in the flexibility and strength of the lower extremities between the two legs or between the agonist and antagonist muscles. It is, however, hard to know which agonist or the antagonist muscles in the legs are stronger or weaker. The reason is when a soccer player kicks a ball using the dominant extremity, the other leg is used to support the body weight (Oshita and Yano, 2010).

Strength and flexibility asymmetry of joints or extremities can lead to improper control of body movement (Grygorowicz et al., 2010). One of the first studies in this field was carried out by Knapik et al. (1991). The athletes in their study reported a higher frequency of lower extremity

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injuries when the right hamstrings were 15% stronger than the left hamstrings at 180°/s, while the right hip extensor was 15% more flexible than the left hip extensor and knee ratio of less than 0.75 at 180°/s. These results revealed that strength and flexibility asymmetries were negatively associated with lower body injuries in female collegiate athletes. Rahnema et al. (2005) reported that knee flexor muscle strength in the non-dominant leg was more than that of the dominant leg in more than 68% English amateur soccer players. In contrast, Brito et al. (2010) found greater peak torque (PT) in the knee flexors and extensors in the dominant leg than the non-dominant leg in sub-elite male soccer players. These conflicting results necessitate further investigation in this area.

Hamstring to quadriceps strength ratio (Hcon/Qcon) between knee extensors and flexors are implicated as an important factor in the predictions of knee function and injuries (Kim and Hong, 2011). Researchers across many sports regard the value of 0.6 as normative for the conventional strength ratio (CSR) at 60°/s which increases up to 0.8 with increased movement velocity (Hewett et al., 2008; Grygorowicz et al., 2010; Hadzic et al., 2010). It has been suggested that the CSR of less than 0.6 would indicate a strength imbalance between the quadriceps and hamstrings which could predispose one to injury (Tourny-Chollet et al., 2000). The results of such testing which used the CSR and dynamic control ratio (DCR= eccentric PT of hamstrings/ concentric PT of quadriceps) to describe muscle balance can be used in knee injury prevention (Grygorowicz et al., 2010; Fousekis et al., 2011). It is estimated that there are 270 million soccer players in the world, 90% of whom are male. Out of this population, young players constitute the majority (54.7%) of the registered male players (FIFA, 2006; Alentorn-Geli et al., 2009). In such a large sports population, injury prevention is important in providing healthcare, enhancing health, as well as decreasing costs for medical care in soccer players (Kiani et al., 2010; Rahnema, 2011).

It is generally accepted that increased flexibility enhances sports performance. Athletes with a high degree of flexibility traditionally present improved proficiency in movements. Flexibility is set by the range of motion (ROM)

available at a joint. Flexibility asymmetry is an important internal risk factor for knee injuries. It has been found that low hip flexibility was associated with an increased risk of injury in soccer players (Arnason et al., 2004; Hrysomallis, 2009). At the same time, flexibility throughout the full ROM must be aptly supported by muscles (Bradley and Portas, 2007; Ozcaldiran, 2008).

In brief, the reviewed studies which aimed to analyse PT and strength ratio in athletes, have shown contradictory results. Additionally, little attention has been paid to the muscle PT, flexibility and strength ratio of male professional soccer players. To our knowledge, only few studies have investigated asymmetry of the knee on professional male soccer players. With respect to the increasing knee injuries in young professional soccer players in the world and relationship between strength deficit, strength ratio and flexibility with knee injuries, the main purpose of the present study was to investigate the bilateral and unilateral asymmetries of strength and flexibility in young male professional soccer players.

Material and Methods

Participants

Thirty-six male young professional soccer players (age: 18.9 ± 1.4 years; body height: 181.3 ± 5.5 cm; body mass: 73.6 ± 6.3 kg) who had played for at least five years, had been regularly training five sessions per week and also had no history of major lower limb injury or disease participated in this study. The participants were selected from three professional teams. Seventeen players had the experience of playing in the national team. All participants were outfield players and members of a professional football club. During the 2011 competitive season, all players participated in official league championships (First Division). The subjects were orally informed about the procedures they would undergo, and each read and signed an informed consent form. The players were chosen by one of the researchers. The study was approved by the Institute of Research Management and Monitoring, University of Malaya and the Sports Centre Research Committee.

Isokinetic test

A Biodex Isokinetic Dynamometer (Biodex Medical Systems, Inc., Shirley, New York,

USA) was used to assess the hamstring and quadriceps strength of the subjects. Before each testing session, the dynamometer was gravitationally corrected in accordance with the manufacturer's recommendations. The subjects performed a general cardiovascular warm-up for at least 5 minutes on a Monark cycle ergometer at a moderate pace and load (50-100 W), followed by 10-minute dynamic stretching concentrating on the lower limbs to prepare the subjects for the assessment of leg torque (Hadzic et al., 2010).

Each subject was seated on the chair and assumed the optimal position to enable the researchers to achieve reliable test results. The subjects were secured with snug straps across the shoulder, chest and hip to limit excessive movement. The cuff of the dynamometer lever arm was attached to proximal malleoli of the ankle. Dynamometer orientation was fixed at 90° and tilted at 0°, while the seat orientation was fixed at 90° and the seatback tilted at 75°-85°. All the seating positions of the subjects were recorded carefully and repeated during post-test. The subjects were instructed to complete 3 trials, two sub-maximal efforts and one maximal effort on the isokinetic machine. The subjects then performed 3 repetitions of knee extension and flexion at each selected angular velocity with a 5 s rest interval in between. They were also given a 1 min rest between different angular velocities and a 3 min break when the machine setting was changed for the opposite leg. The order of testing was randomized for the dominant and non-dominant legs. Encouragements by verbal coaching and visual feedback were given to all subjects to help them concentrate on the quality of their movements. All isokinetic contractions performed on the dynamometer at a speed of 60°/s (slow velocity), 180°/s (medium velocity) and 300°/s (high velocity), through a knee range of motion of 0° (flexed) to 90° (full extension) (Masuda et al., 2005; Zakas, 2006; Fousekis et al., 2010). The conventional strength ratio (CSR) was evaluated by concentric PT of hamstrings divided by concentric PT of quadriceps at each angular velocity. The PT (Newton meter) values were recorded for comparison.

Hip flexibility

The flexibility of the participants' hip joint was measured using a standard goniometer (ISOM 12", Baseline NY) according to the method

described by Norkin et al. (2003). The subjects were laid on a flat surface in a supine position with legs extended. The axis of the goniometer was placed at the greater trochanter of the femur. A strap was used around the pelvis to minimize lumbosacral movement which may have influenced the results. The right leg was passively lifted to the maximum range by the examiner while keeping the knee of the left leg on the flat surface. The examiner also allowed the knee of the right leg to flex passively during the motion. The right leg was kept fixed at maximum hip flexion and the angle between the moveable arm of goniometer and leg was recorded for hip flexibility. The reading was recorded when tightness was felt by the subject and concurred by the examiner. The average of three attempts was used for analysis. This test was performed on the opposite leg to assess the flexibility of both legs (Rahnama et al., 2005; Manning and Hudson, 2009).

Musculoskeletal abnormality

In this study, musculoskeletal abnormality of knee muscles was defined as a bilateral strength imbalance of more than 10% (Dauty et al., 2003; Rahnama et al., 2005).

.Statistical analysis

For data analysis and to compare the PT and CSR among velocities (60°/s, 180°/s, 300°/s) and legs (dominant leg, non-dominant leg) a 3 x 2 (speed vs leg), repeated measures ANOVA was used. To compare DCR and flexibility between the dominant and non-dominant legs, a paired sample *t*-test was used. The single *chi*-square statistic was calculated to compare the observed frequencies of strength deficit. Furthermore, the Kolmogorov-Smirnov (KS) was employed for assessing normality of the distribution of scores. The Levene's test was used to assess homogeneity of variance between groups. A significant level was accepted at the 95% confidence level for all statistical parameters ($p < 0.05$).

Results

Comparison of PT between dominant and non-dominant legs

Means and SD of peak torque of the hamstring and quadriceps muscle groups in the dominant and non-dominant leg are presented in Table 1. The PT of both muscles in the non-dominant leg at all angular velocities showed

higher tendency than the dominant leg. However, no significant differences were found between the dominant and non-dominant legs in the PT of quadriceps muscles ($F_{1,35}=1.05$, $p=0.311$) nor hamstring muscle ($F_{1,35}=1.63$, $p=0.209$). Repeated measures ANOVA results showed significant differences of PT among three angular velocities in the quadriceps ($F_{2,34}=176.4$, $p=0.001$) and hamstring muscles ($F_{2,34}=48.3$, $p=0.001$).

Comparison of deficit between dominant and non-dominant legs

The profile of deficits in the quadriceps and hamstring muscles is shown in Table 2. Deficits were abnormal at all angular velocities (more than 10% difference). Only one player was found normal at all angular velocities of knee muscles, but 35 players (97.2%) were found to have at least one musculoskeletal abnormality of more than 10% at one or more angular velocities. Chi-square showed a significant difference only in

hamstring muscles at 180°/s angular velocity ($p=0.008$).

Comparison of strength ratio between dominant and non-dominant legs

No significant difference ($p>0.05$) was found between dominant and non-dominant legs in CSR, DCR and F/S ratio (muscles peak torque at 60°/s / muscles peak torque at 300°/s). The profile of the strength ratio is shown in Table 3. There was a significant difference between angular velocities in CSR ($F_{2,34}=22.9$, $p=0.01$). In all cases PT were highest at slow velocities (60°/s), followed by medium velocities (180°/s), and lowest at high velocities (300°/s).

Hip joint flexibility between dominant and non-dominant legs

A significant difference was revealed ($t=4.7$, $p=0.001$) between the mean hip joint flexibility of the dominant and non-dominant legs ($108.8 \pm 10.7^\circ$ versus $104.6 \pm 9.8^\circ$, respectively). In this case the flexibility in the non-dominant leg was lower than that of the dominant leg (Figure 1).

Table 1

Isokinetic peak torque in quadriceps and hamstring muscles (values are mean $\pm$ SD), and percentage of change (Δ) [values are mean (95% CI)] of dominant to non-dominant legs.

	Dominant (Nm)	Non-dominant (Nm)	$\Delta\%$ (95% CI)	p
QCon60°/s	201.8 $\pm$ 47.8	209.3 $\pm$ 50.5	-7.5(-17.9 to 2.9)	p= 0.311
QCon180°/s	129.2 $\pm$ 37.9	129.8 $\pm$ 37.2	-0.64(-8.2 to 6.2)	
QCon300°/s	93.2 $\pm$ 30.6	95.8 $\pm$ 30.2	-2.6(-8.5 to 3.2)	
HCon60°/s	100.1 $\pm$ 27.6	102.3 $\pm$ 30.5	-2.1(-10.7 to 6.4)	p= 0.209
HCon180°/s	65.5 $\pm$ 25.6	70.8 $\pm$ 21.1	-5.3(-10.2 to -0.42)	
HCon300°/s	66.8 $\pm$ 25.1	67.9 $\pm$ 24.8	-1.1(-5.7 to 3.4)	

Q = Quadriceps muscles; H = Hamstring muscles; Con = concentric; Nm = Newton meter; °/s = degree per second; CI= confidence interval.

Table 2

Isokinetic deficit (values are mean $\pm$ SD) in quadriceps and hamstring muscles (statistical values are Chi-square and p-value).

	Deficit (Nm)	Normal		Abnormal		χ^2	p
		Frequency	Percent (%)	Frequency	Percent (%)		
QCon60°/s	13.8 $\pm$ 14.6	20	55.6	16	44.4	$\chi^2=0.44$, p= 0.505	
QCon180°/s	15 $\pm$ 16	20	55.6	16	44.4	$\chi^2=0.44$, p= 0.505	
QCon300°/s	16.8 $\pm$ 16.5	17	47.2	19	52.8	$\chi^2=0.11$, p= 0.739	
HCon60°/s	19.6 $\pm$ 30.3	15	41.7	21	58.3	$\chi^2=1.00$, p= 0.317	
HCon180°/s	21.8 $\pm$ 19.7	10	27.8	26	72.2	$\chi^2=7.11$, p= 0.008*	
HCon300°/s	15.2 $\pm$ 11	15	41.7	21	58.3	$\chi^2=1.00$, p= 0.317	

Q= Quadriceps muscles; H = Hamstring muscles; Con= concentric; Nm= Newton meter; °/s = degree per second; χ^2 = Chi-square; * $p<0.05$.

Table 3

*Conventional and dynamic control ratio in dominant and non-dominant legs
(values are mean $\pm$ SD), and percentage of change (Δ) (95% CI)
of dominant to non-dominant legs.*

	Dominant	Non-dominant	$\Delta\%$ (95% CI)	p-value
Conventional ratio				
H/Q _{Con} 60°/s	0.50 ± 0.11	0.50 ± 0.14	0.001(-0.04 to 0.05)	p= 0.30
H/Q _{Con} 180°/s	0.51 ± 0.13	0.56 ± 0.14	-0.05(-0.09 to -0.009)	
H/Q _{Con} 300°/s	0.74 ± 0.22	0.75 ± 0.26	-0.001(-0.05 to 0.04)	
Fast/Slow speed ratio				
F/S Quadriceps	2.3 ± 0.9	2.4 ± 1.3	-0.10(-0.3 to 0.9)	p= 0.36
F/S Hamstring	1.6 ± 0.7	1.7 ± 1.1	-0.08(-0.4 to 0.2)	p= 0.53
Dynamic control ratio				
Hecc/Q _{CON} 120°/s	0.74 ± 0.35	0.75 ± 0.33	-0.01(-0.11 to 0.10)	p= 0.81

Conventional ratio (concentric knee flexion / concentric knee extension);

F/S =Fast/Slow speed ratio (muscles peak torque at 60°/s / muscles peak torque at 300°/s);

Dynamic control ratio= eccentric PT of hamstrings / concentric PT of quadriceps;

Q= Quadriceps muscles; H= Hamstring muscles; Con=concentric;

Nm= Newton meter; °/s= degree per second.

Figure 1

Flexibility in the dominant and non-dominant leg.

Higher degree of flexibility is shown in the dominant leg (p <0.05).*

Discussion

The aim of this study was to investigate the bilateral and unilateral asymmetries of strength and flexibility in young male professional soccer players. Peak torques in the non-dominant leg at all angular velocities seemed

higher than the dominant leg, however, no significant differences were revealed. These results are in agreement with the study of Rahnama et al. (2005) that reported no significant differences between the two legs in knee extensors at three different velocities (60, 120, 300°/s) among elite soccer players. Tourny-Chollet et al. (2000)

investigated 21 (22.0 ± 2.95 years) amateur female soccer players. Their results showed a significant difference at medium speed between hamstring muscles in the dominant and non-dominant legs. Tourny-Chollet et al. (2000) concluded that the knee flexor of the dominant leg tended to be stronger than that of the non-dominant leg. The finding is, however, in contrast with that of the present study. These conflicting results may be caused by the differences in subjects' characteristics such as the level of play, age and gender. Gender-related factors include anatomy, hormonal profile, ligament laxity, and the effect of menstrual cycles on the knee strength. Typically women have a laxity of the ligaments around the knee joint (Loes et al., 2000; Dugan, 2005) which may impact upon knee strength.

The results showed that strength deficits were abnormal (more than 10%) at all angular velocities. The strength deficit is defined as the difference between the strength of muscles of opposite extremities. These results are parallel with those studies that found a majority of soccer players have bilateral strength differences (Ekstrand and Gillquist, 1982; Chin et al., 1994; Rahnama et al., 2005). The strength deficit of more than 10% contributes to a knee risk factor (Fousekis et al., 2010; Brito et al., 2010). In a sport with asymmetric kinetic patterns, more emphasis is given to one side of the legs (Schiltz et al., 2009). According to Iga et al. (2009), soccer players almost never use both legs with equal emphasis. Soccer players' preference to use one side more than the other is related to hemispheric dominance of the brain in the opposite side. This is the possible cause for the deficit abnormality in professional soccer players.

No difference was observed in CSR, DCR and F/S speed ratios between the dominant and non-dominant legs, although the non-dominant leg seemed to have higher ratios. Brito et al. (2010) studied isokinetic knee strength ratio in sub-elite male soccer players, and their results showed that the ratio in the non-dominant leg is more than that in the dominant leg. They found that hamstrings' peak torque of the non-dominant leg is stronger than in those of the dominant leg (Bruto et al., 2010). The conventional strength ratio is calculated as peak torque of hamstrings divided by that of quadriceps muscles. Increasing flexor PT improves the knee strength ratio at this

angular velocity. These conflicting results may be caused by the differences in the level of play of the subjects. Professional soccer players have higher quadriceps strength than non-professional players (Gil et al., 2010).

The results of the present study showed the CSR (normal average; 0.61, 0.72, 0.78 at 60°/s, 180°/s and 300°/s, respectively) and DCR (normal average >1.0) of the players were below the normal average values at various angular speeds which predispose the players to knee injuries. Kim and Hong (2011) studied the National College American Association (NCAA) athletes and found an association of lower than 0.6 of the CSR at 60°/s and non-contact leg injuries, suggesting the significant contribution of hamstring to quadriceps imbalance to non-contact leg injuries. Fousekis et al. (2011) measured intrinsic risk factors during pre-season in 100 professional soccer players and found players with eccentric hamstring strength asymmetries were at greater risk of hamstring strain while players with eccentric strength and flexibility asymmetries in their quadriceps were at greater risk of quadriceps strain. The anterior cruciate ligament (ACL) and hamstring become more susceptible to injury with a mismatch of hamstring to the quadriceps strength ratio. This is because the strength of hamstring is protective against anterior translation of the tibia on femur which occurs during landings and sudden changes in direction. A lower hamstring to quadriceps strength ratio allows higher shear forces on the ACL during these activities. Furthermore, hamstrings strain which commonly follows eccentric lengthening during the terminal swing can be attenuated by increasing the hamstrings strength (Holcomb et al., 2007).

In this study we found that the hip flexibility in the dominant leg was significantly higher than that in the non-dominant leg. The dominant leg is used to handle an object or to lead out, while the non-dominant leg has the main role of providing postural support. This definition of footedness is commonly accepted by researchers (Hardt et al., 2009). Soccer players use one favoured foot unilaterally for kicking the ball (Rahnama et al., 2005; Fousekis et al., 2010). This preference is a possible cause of an asymmetry in flexibility. Professional soccer players can perform a higher Dynamic Range of Motion of the hip joint

during an instep kick after dynamic stretching (Amiri-Khorasani et al., 2011). Kicking by the dominant leg is repeated many times in soccer and it is the same as dynamic stretching that may be caused by higher flexibility in the dominant leg. However, we found that the non-dominant leg has lower flexibility which may lead to injury. Gabbe et al. (2005) showed that decrement in quadriceps flexibility is a predictor to hamstring injury. Worrel et al. (1991) found that the hamstring in the injured group was less flexible than the non-injured group, and that the injured leg was less flexible than the bilateral side. It should be noted that the injured group recruited in his study were those with history of hamstring injury. It is known that hamstring tightness is a risk factor to hamstring injury (Verrall et al., 2001).

There were significant differences between different angular velocities of knee muscles in the dominant and non-dominant legs. The result indicated that the high PT was at the slow speed (60°/s) and the low PT at the higher speed (300°/s). These results are in agreement with Kofotolis and Kellis' (2007) findings. Increasing angular velocity had a significant effect on the PT in both legs. Hill's curve explaining force-velocity showed that muscle fibres produce less contraction while the speed of contraction increases (Malý et al., 2010). The time available for contact between actin and myosin filaments decreases with increasing velocity of concentric activity (Huxley model); thus, period of the contact phase reduces in the overall cycle. Cross-bridges have to be re-released shortly after their connection without enough time to produce

power, so the proportion of combined bridges in the muscle declines, and produces lower strength (Malý et al., 2010). Compressive and translation forces across a joint vary with speed. Slower speeds have more compressive force than faster speeds. More motor units can be recruited at slower speeds than higher speeds allowing more torque production (Bottinelli et al., 1996).

Conclusion

Soccer players usually have some level of musculoskeletal abnormalities and professional soccer training should aim to improve the flexibility of both dominant and non-dominant legs. It is common that the non-dominant leg is less flexible compared to the dominant leg; hence, more emphasis and vigilance should be directed at more balance flexibility. The findings of this research can be helpful for coaches and trainers who can strategize training programs to improve balance and strength of young professional soccer players. The results of the present study support the fact that professional soccer training programmes and competitions at professional levels can affect the strength of the knee joint muscles. These results affirm the possibility that the unique muscle-loading patterns experienced in soccer over time, together with the superior use of the dominant leg, may result in the bilateral asymmetrical increase of the concentric strength of the quadriceps muscles in the dominant kicking leg. The present findings reveal that physical performance and movement pattern experienced during soccer may negatively change the bilateral deficit, but do not have significant effect on the PT, CSR and DCR.

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Cardiorespiratory Fitness and Motor Skills in Relation to Cognition and Academic Performance in Children – A Review

by
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Different elements of physical fitness in children have shown a declining trend during the past few decades. Cardiorespiratory fitness and motor skills have been associated with cognition, but the magnitude of this association remains unknown. The purpose of this review is to provide an overview of the relationship of cardiorespiratory fitness and motor skills with cognitive functions and academic performance in children up to 13 years of age. Cross-sectional studies suggest that children with higher cardiorespiratory fitness have more efficient cognitive processing at the neuroelectric level, as well as larger hippocampal and basal ganglia volumes, compared to children with lower cardiorespiratory fitness. Higher cardiorespiratory fitness has been associated with better inhibitory control in tasks requiring rigorous attention allocation. Better motor skills have been related to more efficient cognitive functions including inhibitory control and working memory. Higher cardiorespiratory fitness and better motor skills have also been associated with better academic performance. Furthermore, none of the studies on cardiorespiratory fitness have revealed independent associations with cognitive functions by controlling for motor skills. Studies concerning the relationship between motor skills and cognitive functions also did not consider cardiorespiratory fitness in the analyses. The results of this review suggest that high levels of cardiorespiratory fitness and motor skills may be beneficial for cognitive development and academic performance but the evidence relies mainly on cross-sectional studies.

Key words: physical fitness, movement skills, physical activity, children, scholastic achievement.

Introduction

Fewer than 20% of children meet the recommendations for health enhancing physical activity: at least 60 minutes of moderate to vigorous intensity physical activity, preferably on every day of the week (Verloigne et al., 2012). Furthermore, a decreasing trend in cardiorespiratory fitness has been documented (Tomkinson and Olds, 2007). Evidence indicates a similar trend in mastery of fundamental motor skills (Hardy et al., 2011).

Concerns have arisen as to whether today's lifestyle has a similarly negative effect on children's metabolic, cardiovascular, and brain health as it has on adults (Hillman et al., 2008). Physical activity has been found to be a foundation of development and reinforcement of

motor skills (Riethmuller et al., 2009). Moreover, children with higher physical activity level also have a higher level of cardiorespiratory fitness, although the effect of physical exercise on cardiorespiratory fitness is smaller in children than in adults (Rowland, 2007). In addition, a higher level of physical activity has been related to better academic performance and executive functions in children and adolescents (Hillman et al., 2008). Executive function is an umbrella term for goal-oriented mental processes, which include planning, organising, behavioural inhibition, and working memory processes.

It is hypothesised that a positive effect of physical activity on cognitive functions is partly caused by physiological changes in the body such as increased levels of brain-derived neurotrophic factor (BDNF), that facilitates learning and

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maintains cognitive functions by improving synaptic plasticity and acting as a neuroprotective agent, increased brain circulation and improved neuroelectric functionality (Hillman et al., 2008). In animal studies it has been shown that different kinds of activities cause different adaptations in the brain. Endurance exercise is shown to increase capillary density (angiogenesis) and thereby to increase the brain blood flow whereas motor exercises are shown to cause synaptogenesis or an increased number of synapses (Adkins et al., 2006). Therefore, cardiorespiratory fitness and motor skills may be differently related to cognition and academic performance among children. Although higher physical activity level in general has been linked to improved cognitive performance, only few studies have compared aerobic and motor exercise in relation to cognitive functions among children and therefore, it is appropriate to compare cardiorespiratory fitness and motor skills although those measures are affected by maturation and genetic factors (Malina et al., 2004).

As children are becoming increasingly sedentary and unfit, it is important to recognise effective interventions to improve metabolic, cardiovascular, as well as cognitive health. The purpose of the present review is to summarise the evidence of associations of cardiorespiratory fitness and motor skills with some important components of cognition and brain functioning that are linked to academic performance among children up to 13-years of age. Also relevant literature of associations of cardiorespiratory fitness and motor skills with academic performance is described. These data is accompanied by the existence of physical or motor activity studies that report measures of cardiorespiratory fitness and motor skills. In addition, factors that may confound these results are discussed.

Inhibitory control

Inhibitory control is the core of the higher cognitive functions called the executive control. Inhibitory control refers to higher order mental processes that are related to the control of attention, behaviour and emotions and involves mainly the neural networks in the prefrontal and parietal cortices (Diamond, 2013). Inhibitory control includes a selective attention to the

requisite stimulus despite inappropriate or interfering stimuli and maintenance of information in working memory. Among children, inhibitory control is shown to be an important predictor of academic performance but also physical and mental health in adulthood and thereby, it is an important component of childhood cognitive development (Diamond, 2013).

The Eriksen flanker task is one of the most used tests for inhibitory control among children in fitness studies. The flanker task requires the child to identify as quickly and accurately as possible the direction of the centrally positioned arrow in either congruent (e.g. < < < <) or incongruent (e.g. < < > > >) conditions. The demands of inhibitory control can be further increased using incompatible conditions. That is, the child is instructed to answer the opposite direction from the direction that the centrally presented arrow is pointing.

Evidence suggests that high levels of cardiorespiratory fitness is associated with a better response accuracy in the flanker task (Chaddock et al., 2012a; Chaddock et al., 2012b; Hillman et al., 2009; Pontifex et al., 2011; Voss et al., 2011) (Table 1). Moreover, some studies indicate that compared to unfit children, highly fit children are more accurate in the incongruent condition (but not in congruent condition) and have less variability in the response accuracy and reaction times in the flanker task conditions that involved a variable amount of interference (Pontifex et al., 2011; Voss et al., 2011).

Improved flanker task accuracy is accompanied by more efficient brain activation. Studies using event-related brain potentials (ERP) have shown that highly fit children have better inhibitory control and exhibit larger P3 amplitudes than unfit children (Hillman et al., 2009; Pontifex et al., 2011) (Table 1). The P3 is a positive-going component that is believed to reflect a subject's attention to stimuli and processing speed. A larger P3 amplitude indicates an increased amount of attentional resources allocated towards a stimulus (Hillman et al., 2008). Moreover, highly fit children also have reduced error-related negativity (ERN) amplitude during the flanker task (Hillman et al., 2009). In addition, higher levels of fitness have been related to a larger change in ERN amplitude between the compatibility conditions (Pontifex et al., 2011).

Table 1

Summary of relationship of cardiorespiratory fitness and motor skills with inhibitory control

Reference, country	Design/subjects	Fitness or motor skill	Inhibitory control	Main results
Chaddock et al. (2012a), USA	Cross-sectional / semi-prospective 32 children aged 9–10 years	Maximal treadmill test ^a	Modified flanker task + MRI	HF had better accuracy in congruent and incongruent conditions at baseline than UF. After follow-up, HF showed superior performance in accuracy and RT showing better cognitive control. MRI . HF had larger bilateral putamen and GP volumes and these volumes correlated with response accuracy during incompatible condition. Putamen volumes were directly related to follow-up accuracy and RT in incompatible and compatible conditions
Chaddock et al. (2012b), USA	Cross-sectional 32 children 9–10 years of age	Maximal treadmill test ^a	Modified flanker task + fMRI	No differences in congruent task in activation levels between UF and HF. As cognitive demands increased in the incongruent, relative to congruent, condition, HF showed greater activation in the prefrontal and parietal cortex during early task block. Only HF showed a decrease in these brain areas and maintenance of accuracy
Hillman et al. (2009), USA	Cross-sectional 38 children 9 years of age	Endurance shuttle run test ^b	Modified flanker task + ERP	HF were more accurate across task conditions than UF. Greater P3 amplitude and reduced ERN was observed in HF than UF.
Livesey et al. (2006), Australia	Cross-sectional 36 children 5–6 years of age	MABC	Go/NoGo task, day-night stroop task	Better fine motor skills were associated with shorter reaction times in the Stroop task, but no association with Go/NoGo task performance was found
Pontifex et al. (2011), USA	Cross-sectional 48 children 10 years of age	Maximal treadmill test ^a	Modified flanker task + ERP	HF showed greater response accuracy in compatible and incompatible condition than UF. Difference was larger in incompatible condition indicating that the harder the task, the larger the difference. HF demonstrated a larger change in P3 amplitude and ERN between compatibility conditions than UF
Roebbers and Kauer (2009), Switzerland	Cross-sectional 112 children 7.5 years of age	Jumping moving sideways, postural flexibility, pegboard	Flanker task, Simon Task, Cognitive flexibility task (RT)	Pegboard test performance was directly associated with reaction time in Simon and Cognitive flexibility tasks. Performance in the postural flexibility test was directly related to reaction times in Simon task. Performance in the sideways moving task was directly associated with reaction times in Cognitive flexibility task. Jumping was directly associated with reaction times during flanker, Simon, and Cognitive flexibility tasks
Voss et al. (2011), USA	Cross-sectional 28 children 9–10 years of age (25 young adults 18–30 years served as a control)	Maximal treadmill test ^a	Flanker task + fMRI	HF exhibited greater overall accuracy percentage and greater accuracy in incongruent condition than UF. HF also showed less variation between congruent and incongruent condition than UF. fMRI . Children showed poorer activation than young adults. HF demonstrated more activation of brain regions involved in cingulo-opercular network

HF, Highly fit children. UF, unfit children. fMRI, functional magnetic resonance imaging.

MRI, magnetic resonance imaging. GP, globus pallidus. ERP, event-related brain potential.

RT, reaction time. ERN, error-related negativity.

^aDivided into > 70th and < 30th percentile according to child's VO_{2max} .

The ERN is an ERP component that has been related to erroneous responses in tasks that emphasise reaction time. Some evidence indicates that the ERN is related to known mistakes and is therefore a marker for error detection and

compensation, that is, action monitoring (Gehring et al., 1993). Furthermore, increased ERN may also be associated with an increased level of response conflict (Gehring and Fencsik, 2001) and reduced ERN may reflect more efficient action

monitoring (Gehring et al., 1993). Thus, these results indicate that higher levels of cardiorespiratory fitness is related to a better attention allocation, action monitoring and increased modulation of cognitive control.

Cross-sectional studies using functional magnetic resonance imaging technique (fMRI) indicate that children with high levels of fitness exhibit more efficient neural activation and cognitive adaptation during the flanker task compared with less fit children (Chaddock et al., 2012b; Voss et al., 2011) (Table 1). Findings suggest that cortical activation does not differ between highly fit and unfit children during the congruent condition, but when cognitive demands increase during the incongruent condition, highly fit children maintain their response accuracy and exhibit greater activation in the prefrontal and parietal cortices in the early task period and reduced activation in the later periods indicating more effective cognitive flexibility (Chaddock et al., 2012b). Another study showed increased activation in the prefrontal cortex and decreased activation in the posterior parietal cortex of highly fit children during the flanker task (Voss et al., 2011). Moreover, highly fit children showed lower or the same activation than unfit children in the left central opercular cortex in the incongruent condition of the flanker task. Interestingly, higher activation was related to task performance only among highly fit children. Of these brain regions, the dorsolateral prefrontal cortex is involved in the manipulation of task relevant information within working memory (Diamond, 2013) and is related to top-down regulation of executive functions (MacDonald III et al., 2000). Also, the parietal cortex is involved in inhibitory control (Brass et al., 2005), and like the dorsolateral prefrontal cortex, parietal cortex is important for the working memory function (Hillman et al., 2008). Thus, the findings indicate that 9 to 10-year-old children with superior cardiorespiratory fitness are capable of activating their frontal and parietal circuitry in demanding cognitive tasks more efficiently than their less fit counterparts.

Moreover, some evidence indicates that better response accuracy among highly fit children in comparison with unfit children is related to larger subcortical structure volumes (Table 1). Chaddock et al. (2012a) found that

compared to unfit children, highly fit children had larger bilateral putamen and globus pallidus volumes and greater response accuracy during a modified flanker task in the baseline as well as in the one-year follow-up. Highly fit children also had shorter reaction times in the follow-up. The authors concluded that greater volumes of the putamen and the globus pallidus were associated with better cognitive control.

Also motor skills have been studied in relation to cognitive control. Among studies, the results are inconsistent and the magnitude of associations is dependent on the assessment of inhibitory control. Better manual dexterity (but not throwing accuracy or balance) has been associated with shorter reaction times in the modified day-night Stroop task whereas motor skills were not related to the reaction times during the Go/NoGo task (Livesey et al., 2006) (Table 1). Better whole body coordination (including sideways jumping speed and better ability to quickly change posture from lying down to an upright position and back to lying down i.e. postural flexibility) and better manual dexterity have been linked to shorter reaction times of correct responses during the Simon task (Roebbers and Kauer, 2009). In addition, a better sideways jumping performance was associated with shorter reaction times in the flanker task, whereas other whole body coordination and manual dexterity skills were not related to the flanker task performance (Roebbers and Kauer, 2009). However, these studies did not investigate relationships between motor skills and response accuracy. There is some vagueness whether reaction time is an appropriate measure of inhibitory control. Evidence suggests that children with high and low cardiorespiratory fitness did not differ in their reaction times in the flanker task but children with higher levels of fitness have better response accuracy than those with lower levels of fitness (Hillman et al., 2009; Pontifex et al., 2011).

Working and short term memory

Working memory involves holding and manipulating the information in mind and relies on dorsolateral prefrontal cortex. Working memory involves also associative or relational memory. Relational memory involves learning about the relationship between two stimuli. In

contrast, short term memory involves keeping information in mind without manipulating it, thus learning the properties of the stimulus (i.e. item memory). Short term memory does not need involvement of dorsolateral prefrontal cortex and it relies on ventrolateral prefrontal cortex (Diamond, 2013). In the behavioural point of view, working memory has been linked to academic performance among children. Moreover, inhibitory control is linked to working memory, thus inhibitory control is shown to support the working memory processes (Diamond, 2013).

The current evidence suggests that higher levels of cardiorespiratory fitness are related to a better relational memory and thereby hippocampal encoding (Chaddock et al., 2010; Monti et al., 2012) (Table 2). However, these studies did not find a relationship between cardiorespiratory fitness and item memory. In addition, a larger bilateral hippocampal volume has been related to a better relational memory and based on mediating analyses, bilateral hippocampal volume is shown to mediate the relationship between cardiorespiratory fitness and relational memory (Chaddock et al., 2010b) (Table 2). Moreover, Monti et al. (2012) extended these cross-sectional designs by conducting a longitudinal analyses to study whether nine-month aerobic training was related to working memory performance and eye movement patterns during a memory task in the follow-up. Children in the training group increased their VO₂max percentile whereas the VO₂max percentile among children in the control group slightly decreased. Children in the training group had a longer viewing time for displayed pictures during relational memory tasks that required the children to encode and correctly retrieve self-chosen sets of scenes and faces. In contrast, no differences in viewing time were observed during an item memory task that required retrieval of familiar faces without any need to relate them to a scene. Moreover, they found no differences in task accuracy or reaction times. Although no fitness differences were observed in response accuracy, these results indicated that increased cardiorespiratory fitness is related to more efficient hippocampal encoding. Evidence suggests that improved hippocampal encoding alone is not enough to elicit correct responses

during relational memory tasks; high performance on tasks requires prefrontal cortex activation and efficient hippocampal prefrontal cortex connectivity (Hannula and Ranganath, 2009). Moreover, these results by Monti et al. (2012) should be interpreted cautiously because there was no baseline assessment for memory performance.

In addition, findings by Niederer et al. (2011) support other studies on a non-significant relationship between cardiorespiratory fitness and item memory (Table 2). However, Kamijo et al. (2011) conducted a RCT study whether aerobic exercise training over a nine-month period would have an effect on item memory and ERP component called contingent negative variation (CNV). The CNV reflects cognitive, motor, and sensory processes in preparation for an upcoming stimulus. The CNV includes at least two components, initial and terminal waves, which have different functions (Brunia and van Boxtel, 2001). The initial CNV wave has been associated with stimulus orientation (Weerts and Lang, 1973) whereas the late wave is mainly related to motor and response preparation (Brunia and van Boxtel, 2001). Kamijo et al. (2011) adopted a modified Stenberg task to assess a delayed recognition of previously presented arrays of letters. After the intervention, only the training group (relative to the control group) improved their VO₂max by 4.2 ml/kg/min, as well as their response accuracy in comparison to pre-intervention accuracy. Improved accuracy was observed only in the task condition, where the child was required to encode an array of three letters; no significant improvement was found when one or five letters were encoded. The exercise group also exhibited greater frontal initial CNV (iCNV) amplitude compared with controls on post-intervention testing. The authors speculated that cardiorespiratory fitness-related increases in iCNV amplitude indicate an increased efficiency of anticipatory attention and pronounced top-down control. However, these results concerning the effect of cardiorespiratory fitness on item memory are in contrast to other studies showing no relationship between cardiorespiratory fitness and item memory. Therefore, improved item memory may be due to physical exercise per se, without a mediating effect of cardiorespiratory fitness.

Table 2*Summary of relationship of cardiorespiratory fitness and motor skills with memory functions*

Reference, country	Design/subjects	Fitness or motor skill	Memory	Main results
Chaddock et al. (2010), USA	Cross-sectional 59 children 9–10 years of age	Maximal treadmill test ^a	Item and relational memory paradigm + MRI	HF had greater bilateral hippocampal volumes and better relational memory than UF; bilateral hippocampal volume mediated the relationship between fitness and relational memory. No association between fitness and item memory was found
Kamijo et al. (2011), USA	RCT (9 months) 36 children 7–9 years of age	Maximal treadmill exercise test to assess VO_{2max} before and after exercise intervention	Modified Stenberg task for item memory + ERP	Increased fitness after the intervention was associated with improved overall accuracy in memory task. The intervention group exhibited greater iCNV amplitude in comparison to control group at the end of the intervention period
Monti et al. (2012), USA	Longitudinal (9 months) 44 children 9 years of age, cognitive assessment of only in the follow-up	Maximal treadmill exercise test to assess VO_{2max} before and after exercise intervention	Working memory task for non-relational and relational memory, eye-movement tracking	Children in the exercise intervention group showed longer viewing times for the related pictures than control group during relational memory task. No differences during non-relational memory task accuracy. No differences in performance accuracy or reaction times between intervention and control groups
Niederer et al. (2011), Switzerland, Germany	Cross-sectional /longitudinal (nine-month follow-up) 245 children 5.2 years of age	Agility, dynamic balance, multistage shuttle run test	Item memory	Agility was associated with item memory in cross-sectional analyses and baseline balance predicted improvement in item memory longitudinally
Pangelinan et al. (2011), USA	Cross-sectional 172 children 6–13 years of age	Purdue pegboard task	Spatial working memory + MRI	Pegboard test performance was not related to spatial working memory.
Piek et al. (2008), Australia	Cohort study 33 children 6–11 years of age at the follow-up (initial assessment at the age of four months)	Ages and stages questionnaire, McCarron assessment of neuromuscular development	Digit span and letter-number sequencing = working memory index	Early gross motor development predicted working memory
Roebbers and Kauer (2009), Switzerland	Cross-sectional 112 children 7.5 years of age	Sideway jumping, moving sideways, postural flexibility, pegboard	Backward colour recall	Better performance in the postural flexibility test was related to higher performance in memory task
Wassenber g et al. (2005), the Netherlands	Cross-sectional 378 children 6.18 years of age	Maastricht motor test (static balance, dynamic balance, ball skills, manual dexterity)	Auditory item memory	Better qualitative motor skills (i.e. the movement process) were related to a better item memory

HF, highly fit children. UF, unfit children. ERP, event-related brain potential.

iCNV, initial contingency negative variation

^aDivided into > 70th and < 30th percentile according to child's VO_{2max} .

The relationship between motor skills and memory has been investigated using mainly item memory tests. Both, a better whole body coordination and manual dexterity, have been

associated with a better item memory (Niederer et al., 2011; Piek et al., 2008; Roebbers and Kauer, 2009; Wassenberg et al., 2005) (Table 2). Furthermore, some evidence indicates that earlier

gross motor development predict item memory at later years (Piek et al., 2008). Moreover, motor skills may be differently related to working memory depending on whether the assessment of motor skills is an outcome oriented (e.g. distance in the standing long jump) or a process oriented (e.g. throwing technique). Wassenberg et al. (2005) demonstrated no relationship between motor test outcomes, but showed a positive relationship between fluency and technique during the motor task and item working memory test performance. Moreover, in one study, more agile children showed superior item recall than their less agile peers. Furthermore, children with better dynamic balance at the baseline showed significant improvement in item memory during a nine-month follow-up (Niederer et al., 2011). However, not all studies have found a relationship between motor skills (manual dexterity) and spatial working memory (Pangelinan et al., 2011) indicating some specificity of effects of cardiorespiratory fitness and motor skills on memory functions.

Academic performance

Academic performance refers to a child's success in school, measured by grade point averages or the child's meeting standards of various achievement tests. In addition to plain academic knowledge, grade point averages usually contain information about class attendance or classroom behaviour, whereas standardised tests rely on academic knowledge. Academic performance is affected by inhibitory control and working memory performance, as well as efficiency of other aspects of executive control (Diamond, 2013).

Cross-sectional studies suggest that higher cardiorespiratory fitness is related to better results and higher scores in standardised achievement tests (Van Dusen et al., 2011; Welk et al., 2010; Wittberg et al., 2010, Davis and Cooper, 2011) and to higher scholastic ratings (Dwyer et al., 2001) in comparison to peers with a lower fitness level (Table 3).

Most studies have addressed the relationship between cardiorespiratory fitness and academic performance using field-based exercise tests and cut-offs for cardiorespiratory fitness (Van Dusen et al., 2011; Welk et al., 2010). These studies indicate that achieving a certain

cardiorespiratory fitness level is significantly and positively associated with improved academic performance (Table 3). Studies that have adopted linear methods also indicate that higher cardiorespiratory fitness is related to better academic performance (Dwyer et al., 2001; Wittberg et al., 2010; Davis and Cooper, 2011). Furthermore, these studies suggest that the degree of the association between cardiorespiratory fitness and academic performance depends on the assessment of cardiorespiratory fitness. Whereas Dwyer et al. (2001) did not find a significant association between academic performance and cardiorespiratory fitness estimated by a cycle ergometer, a significant association was found when they used time spent on a 1.6 km running test as a measure of cardiorespiratory fitness. Instead, one study found that low running time in one mile test was associated with better academic performance, whereas no association was found between endurance shuttle run test and academic performance among 9- to 13-year-old boys. In contrast, the association between cardiorespiratory fitness and academic performance was only found with endurance shuttle run performance in girls (Wittberg et al., 2010) (Table 3).

In contrast to studies concerning the relationships of cardiorespiratory fitness to academic performance that have used grade point averages and standardised achievement tests as measures of academic performance, associations of motor skills with academic performance include measures of grade point averages, estimated academic performance by a class-room teacher and reading skills. The evidence indicates that children with better overall perceptual motor abilities have better grade point averages than children with lower perceptual motor skills. Positive associations have also been found between manual coordination, static balance, asynchronous movement, and grade point averages in girls who were 10–11 years of age (Nourbakhsh, 2006).

Evidence from longitudinal studies indicates that only fine motor skills in young childhood predict improvement in reading and math skills in later years (Pagani et al., 2010). However, none of the studies involved an analysis of the possible relationship between current

motor skills, cognition, and academic performance.

Intervention studies aimed at improving motor skills have documented a weak positive connection between motor skill training and improved academic performance and reading skills among school-aged children (Ericsson, 2008;

Uhrich and Swalm, 2007), but the evidence is not consistent (Bassin and Breihan, 1978). Ulrich and Swalm (2007) showed that children who participated in bimanual dexterity training for six weeks improved their reading comprehension, but not reading decoding in comparison with the children in the control group.

Table 3
Summary of relationship of cardiorespiratory fitness and motor skills with academic performance

Reference, country	Design/subjects	Fitness or motor skills assessment	Academic performance assessment	Main results
Bassin and Breihan (1978), USA	Intervention 66 children	Visuomotor activities for trice a week for 20 weeks	Reading achievement	Motor skill based intervention had no effect on reading achievement.
Davis and Cooper (2011), USA	Cross-sectional 170 overweight children 7-11 years	Maximal treadmill test	The Woodcock-Johnson III	Higher levels of cardiorespiratory fitness was associated with better reading and arithmetic performance
Dwyer et al. (2001), Australia	Cross-sectional 7961 children 7–15 years of age	1.6 km, indirect submaximal cycle ergometer exercise test	Scholastic ability rated by 5-point scale	Better performance in the 1.6 km run was associated with higher scholastic ability
Ericsson (2008), Sweden	Intervention study 251 primary school children in Grades 1 to 3	Motor activities for five lessons / week	Swedish (writing and reading), mathematics	Significant association between participation to the intervention and academic performance
Nourbakhsh (2006) Iran	Cross-sectional 400 girls 10–11 years of age	The Oseretsky scale	Grade point average	General static and dynamic coordination, synchronous-symmetrical and asynchronous-asymmetrical movements and total perceptual motor skill correlated positively with grade point average
Pagani et al. (2010), Canada	Cohort study 1145 children (538 boys) 5.4 years of age	Gross motor skills, fine motor skills	Teachers' estimation of academic performance	Fine motor skills at the age of five predicted mathematics, reading, and overall academic performance 24 months later
van Dusen et al. (2011), USA	Cross-sectional 254 743 third to 11th grade students	1 mile run, endurance shuttle run test (lowest quintile vs. highest quintile)	Texas Assessment of Knowledge and Skills (reading and mathematics)	High-fit children had better academic performance, but no differences was found in elementary school
Uhrich and Swalm (2007), USA	Cluster-RCT 41 children 8 years of age	Speed stacking	Gates-MacGinitie Reading Test (decoding, comprehension)	Intervention group performed better in comprehension but no differences were observed in decoding
Welk et al. (2010), USA	Cross-sectional 36 835 students	Endurance shuttle run test, 1.6 km run (meets recommendations vs. does not meet recommendations),	Texas Assessment of Knowledge and Skills; attendance, delinquency	Meeting recommendations for aerobic fitness was associated with better academic performance and better attendance
Wittberg et al. (2010), USA	Cross-sectional 1740 children 9–13 years of age	1 mile run, endurance shuttle run test. (time spent to complete 1 mile; number of circuits in the shuttle run test)	West Virginia Standardized Test	Higher number of circuits in the PACER was associated with better academic performance in girls and faster time in the 1 mile run was associated with higher academic performance in boys

Furthermore, Ericsson (2008) showed that children who were assigned to a physical training programme for motor skills not only improved their motor skills, but also their Swedish language (the first language of the participants) and mathematic performance. However, Bassin and Breihan (1978) documented no effect of twenty-week visuomotor training on reading achievement.

Discussion

The findings presented in this review suggest that both higher levels of cardiorespiratory fitness and better motor skills are linked to a higher cognitive capacity and a better academic performance. However, cardiorespiratory fitness and motor skills may be differentially related to cognitive functions. Higher levels of cardiorespiratory fitness are mainly associated with a higher performance in tasks that require rigorous attention allocation and the use of attention resources in order to prevent undesirable results (Buck et al., 2008; Chaddock et al., 2010a; 2011; 2012; 2012a; 2012b; Hillman et al., 2005; 2009; Niederer et al., 2011; Pontifex et al., 2011; 2012; Voss et al., 2011; Wu et al., 2011) and a higher performance in the memory tests that involves hippocampal encoding (Chaddock et al., 2010b; 2011; Monti et al., 2012). In contrast, it seems that higher levels of cardiorespiratory fitness do not affect the performance on item memory tests. Furthermore, children with high levels of fitness have a better academic test performance than those with lower levels of fitness (Castelli et al., 2007; Davis and Cooper, 2011; Dwyer et al., 2001; Edwards et al., 2011; Eveland-Sayers et al., 2009; Roberts et al., 2010; Van Dusen et al., 2011; Welk et al., 2010; Wittberg et al., 2010).

Better motor skills have been related to a better performance in various cognitive tests including tasks for IQ, attention, inhibitory control, item memory and academic performance (Livesey et al., 2006; Niederer et al., 2011; Nourbakhsh, 2006; Pangelinan et al., 2011; Piek et al., 2008; Roebbers and Kauer, 2009; Wassenberg et al., 2005). Furthermore, evidence indicates that early fine motor skills predict better academic performance later in life (Grissmer et al., 2010; Pagani et al., 2010). However, there may be an overlap between cross-sectional and cohort

studies. If this is the case, children who develop earlier may also be more skilful in later childhood. Although it is inconsistent, some existing evidence indicates that motor skill training can contribute to improved academic skills and academic performance in children (Ericsson, 2008; Urich and Swalm, 2007). Furthermore, only one study has assessed both cardiorespiratory fitness and motor skills, but they were used in separate analyses (Niederer et al., 2011); thus, none of the studies examining this aspect controlled their analyses for cardiorespiratory fitness although it is known that cardiorespiratory fitness is related to motor skills (Lubans et al., 2010).

Regardless of relatedness of cardiorespiratory fitness and motor skills, results summarised in the present review emphasise that children should engage in various physical activities including both quantitative and qualitative aspects to contribute to cognitive development. That is, physical activity should incorporate with activities improving cardiorespiratory fitness and activities that enhance motor skills. However, this conclusion is mainly drawn from cross-sectional studies and, therefore, it cannot be concluded that exercise training to increase cardiorespiratory fitness and motor skills actually contributes to enhanced cognitive performance in children. In addition, this mainly cross-sectional data may be confounded by genetic factors, maturity status and other factors.

Interplay of cardiorespiratory fitness, motor skills, genetics, and maturation

Although cardiorespiratory fitness and motor skills evidently play a role in cognition and academic performance, the extent to which these differences are mediated by genetic or biological factors is unclear. It is known that genetic factors can explain approximately 50% of cardiorespiratory fitness (Malina et al., 2004) and moreover, many childhood cognitive deficits are highly inheritable (Rutter, 2006). Cognitive deficits, such as learning disabilities, are often associated with coordination and motor skill disorders. Some authors have suggested that coordination disorders and learning disabilities may share a genetic cause (Martin et al., 2006). Again, there is some evidence that genetically regulated biological maturation may affect the

relationships presented in this review. Boys who mature early show better motor skills than average and late maturing boys during early adolescence (Malina et al., 2004). However, the association between maturity and motor skills is somewhat mixed in girls (Malina et al., 2004). These results indicate that, at least in boys, biological maturity may confound the relationship between motor skills and cognitive functions. This means that more mature children may have an advanced neuromuscular system, leading them to perform better in motor tests. Moreover, children with older skeletal age, a marker of biological maturity, show better cognitive capacity in comparison to children with younger skeletal age (Goldstein, 1987). Thus, the relationship between motor skills and cognitive functions may be at least partly explained by differences in genetic background and maturation status. In contrast, the majority of studies that addressed relationships between cardiorespiratory fitness and cognitive functioning controlled their data for sexual maturity; that is, children who participated in those studies were classified as prepubertal according to their secondary sex characteristics (Chaddock et al., 2010; 2012a; 2012b; Hillman et al., 2009; Monti et al., 2012; Pontifex et al., 2011; Voss et al., 2011). In those studies, it is less likely that maturation confounded the results. Moreover, although genetic factors may have had an influence on the results presented here, genes usually act in a probabilistic fashion; thus, environment and other factors can downregulate or upregulate gene expression (Rutter, 2006). In this respect, the intervention results (Ericsson, 2008; Kamijo et al., 2011; Uhrich and Swalm, 2007) are encouraging in showing that training which improves cardiorespiratory fitness and/or motor skills may be beneficial for brain function and learning in childhood.

Interplay between cardiorespiratory fitness and motor skills

It is an oversimplification to suggest that only cardiorespiratory fitness or only motor skills are the important determinants of cognitive functions in children. In fact, the evidence suggests that cardiorespiratory fitness and motor skills are positively correlated, suggesting that children with high cardiorespiratory fitness also have better motor skills than those with low

fitness (Lubans et al., 2010). In this respect, it is not known whether exercise training consisting of aerobic exercise (for example treadmill running) without any component of motor skill training improves cognitive functions. Although Kamijo et al. (2011) showed that improved cardiorespiratory fitness enhanced cognitive performance, their intervention also consisted of exercises that potentially improved motor skills and musculoskeletal fitness. Results by Ericsson (2008), in contrast, indicated that children who improved motor skills through increased motor skill training improved their academic performance as well. However, it is likely that children who underwent physical activity intervention also saw an improvement in cardiorespiratory fitness. Thus, although aerobic walking has been related to improved cognitive functions in older adults (Hillman et al., 2008), it remains unclear as to whether simple aerobic exercise (such as walking) or motor skill training without an aerobic component, assists developing cognitive functions and brain health in growing children. On the other hand, it may be the case that aerobic training combined with motor skill training produces the best combination for cognitive development. Exercise training that leads to improved cardiorespiratory fitness creates an environment that supports neural growth and survival via increased levels of nerve growth factors, and motor skill training increases and refines structural efficiency of neural networks in children (Adkins et al., 2006).

Situating the results into the context of the obesity epidemic

In the point of view of public health, the findings reviewed here are of great importance. The number of obese children continues to increase (Janssen et al., 2005), and a growing amount of children and adolescents spend their waking hours in sedentary activities (Verloigne et al., 2012). Moreover, a recent study showed that excess adiposity and especially intra-abdominal adiposity assessed by dual-energy X-ray absorptiometry (DXA) was negatively associated with inhibitory control and academic performance in 7- to 9-year-old children (Kamijo et al., 2012). Studies suggest that obese children have lower cardiorespiratory fitness (Stigman et al., 2009) and poorer motor skills (D'Hondt et al., 2012) in

comparison to their normal weight peers. Moreover, more physical activity leads to decreased adiposity and improved motor skills in young children 0 to 4 years of age (Timmons et al., 2012). This negative relationship between adiposity and cognitive function may be partially explained by the poor development of cardiorespiratory fitness and motor skills through a lack of physically and mentally challenging activities. Moreover, there exists a threat that as younger children increasingly become sedentary and obese, they do not reach the level of physical fitness (including cardiorespiratory and motor components) necessary to support brain health and development. However, physical activity consisting of moderate to vigorous aerobic exercise and demanding motor skill exercises seems to be an effective intervention to enhance cognitive functioning, academic performance and brain health among overweight children (Davis et al., 2011b). The children in the training group, relative to the control group, showed increased activation in the bilateral prefrontal cortex and decreased activation in the bilateral posterior parietal cortex during the antisaccade task (Davis et al., 2011b) indicating more efficient cognitive processes. Unfortunately, the authors did not report task performance in relation to brain activation. Thus, there is some evidence that interventions aimed at increasing children's physical activity levels and improving

cardiovascular and neuromuscular health also have the potential to contribute to cognitive development.

Conclusion

The evidence summarised in the present review suggests that compared to less fit children, highly fit children have larger subcortical brain structures, more efficient brain activation and neuroelectric efficiency during cognitive tasks, superior inhibitory control, working memory, attention and better academic performance. Similarly, children with better motor skills show better inhibitory control, attention capacity and academic performance than children with poorer motor skills. Thus, the evidence suggests that both cardiorespiratory fitness and motor skills play an important role in cognitive development during childhood. It is strongly suggested that children are allowed to get appropriate stimulation from the environment via physical activities in order to improve the functions of their cardiovascular and neuromuscular systems. Besides the known cardiometabolic benefits, developmentally appropriate physical activity may improve brain health and function. There is a need for multidisciplinary studies that assess the interdependent relationships of cardiorespiratory fitness and motor skill with cognitive functions in cross-sectional and longitudinal settings.

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A Reliability of Electromyographic Normalization Methods for the Infrapinatus Muscle in Healthy Subjects

by

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The purpose of this study was to examine the test-retest reliability of normalization methods for the infrapinatus muscle in a group of healthy subjects. Twelve healthy subjects (male=8, female=4) performed the maximal voluntary isometric contraction (MVIC) with examiner's resistance, MVIC with a digital tension-meter (MVIC-DT), and sub-MVIC methods. Surface electromyography (EMG) signals were recorded from the infrapinatus muscles according to normalization methods. Reliability was analyzed using the intra-class coefficient (ICC), standard error of measurement (SEM), and minimal detectable difference (MDD). The results of the present study demonstrated that the sub-MVIC method has excellent test-retest reliability (ICC=0.92) with a relatively small SEM (5.9 mV) and MDD₉₅ (16.4 mV), compared to MVIC-DT (ICC=0.73; SEM=11.2 mV; MDD₉₅: 31 mV) and MVIC-E (ICC=0.5; SEM=15.7 mV; MDD₉₅: 43.6 mV). These findings provide evidence that sub-MVIC is more appropriate for comparing the EMG activity for the infrapinatus muscle as a normalization method. If MVIC for normalization is needed, MVIC-DT is more appropriate than MVIC-E.

Key words: electromyography, infrapinatus muscle, normalization, reliability.

Introduction

The infrapinatus muscle produces an approximation force to resist distraction during an overhead throwing motion (Ballantyne et al., 1993). Also, the infrapinatus provides the primary external rotation force (Terry and Chopp, 2000). Because of its critical role in providing dynamic stability and producing external rotation torque at shoulder joint, many authors have advocated emphasis on infrapinatus muscle strengthening during rehabilitation or athletic conditioning programs in order to enhance muscular strength and endurance (Blackburn et al., 1990; Brewster and Schwab, 1993; Reinold et al., 2004; Townsend et al., 1991).

Previous studies were conducted using surface electromyography (EMG) to measure the muscle activity of infrapinatus through EMG studies in a variety of exercises (Ballantyne et al., 1993; Reinold et al., 2004). A major limitation of kinesiology EMG research is the difficulty in making comparisons between EMG values obtained from identical muscles in different subjects, different muscles from the same subject, or even the same muscle from the same subject on different days. These difficulties may be due to subtle differences in muscle architecture, electrode placement, and electrode construction (Giroux and Lamontagne, 1990; Jonsson and Komi, 1973; Kadaba et al., 1985). To overcome these shortcomings of

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surface EMG, the concept of normalization has been developed to enable comparing EMG signal (Mirka, 1991).

Numerous studies have been performed using maximal voluntary isometric contraction (MVIC) normalization method to identify effect of exercises or intervention for infraspinatus muscle strengthening (Ballantyne et al., 1993; Bitter et al., 2007; Ekstrom et al., 2003). The MVIC normalization technique is the use of the maximal voluntary contraction of a predetermined isometric movement as the reference EMG signal (Hagberg and Sundelin, 1986; Yang and Winter, 1983). The MVIC has the advantage of having a physiological meaning where derived data are expressed relative to the maximum (Allison et al., 1998). To produce MVIC, resistances of examiner's hand or digital tension-meter (DT) have been used as a common method (Kendall and McCreary, 2005; Netto and Burnett, 2006). As the reference value for normalization, MVIC may account for much of the potential variability among recording factors (e.g. skin impedance, electrode position, collection methods and devices, electrode size and pick-up area, etc.). However, the reproducibility of this reference point depends on subject's level of sincerity, motivation, or pain during the exertion. The subjective nature of these exertions may introduce some level of experimental error (Marras and Davis, 2001). Larivière et al. (2002) demonstrated that between-day reliability of MVIC method was poor in the comparison of EMG activities for the back muscles between healthy control subjects and chronic patients with low back pain.

To address these limitations, sub-MVIC is frequently used as a predetermined reference value when MVIC are limited by aging, pain or other symptoms (Allison et al., 1998; Dankaerts et al., 2004; Marras and Davis, 2001). This approach is limited by the difficulty of establishing equivalent sub-maximal loads for different muscles (Allison et al., 1998). To establish equivalent sub-maximal loads, the estimation of the expected maximum contraction, 60% MVIC using isokinetic dynamometer was used to predict a reference point to be used for normalization in the neck and trunk muscles (Burnett et al., 2007; Dankaerts et al., 2004; Marras and Davis, 2001; Netto and Burnett, 2006). Previous studies reported that sub-MVIC are more reliable and are more sensitive than MVIC when

assessing low levels of abdominal muscle activities (Allison et al., 1998; O'Sullivan et al., 1998). Also, Sub-MVIC has been reported to be reliable within-day reliability in healthy subjects when assessing EMG for abdominal wall muscles (Allison et al., 1998; O'Sullivan et al., 1998). However, there is no attempt to investigate sub-MVIC for the infraspinatus muscle, compared to MVIC.

Therefore, the purpose of this study was to examine the reliability of normalization methods for the infraspinatus muscle in a group of healthy subjects. Specifically, MVIC with examiner's resistance (MVIC-E) as a common method, MVIC with digital tension-meter (MVIC-DT), and sub-MVIC methods were examined. The hypothesis of this study was that sub-MVIC method would more reliable than other normalization method.

Material and Methods

Twelve healthy subjects (male=8, female=4) were recruited from the university populations. The characteristics of the subjects are presented in Table 1. There were significant differences in physical characteristics between males and females. Inclusion criteria were 1) ability to perform full shoulder external rotation comfortably, 2) manual muscle testing (MMT) grade was 5/5 (Hislop and Montgomery, 2002; Kendall and McCreary, 2005). Exclusion criteria were past or present neurological, musculoskeletal, or cardiopulmonary diseases that could interfere with shoulder external rotation in the testing position. Before the study, the principal investigator explained all procedures to the subjects in detail. All subjects signed an informed consent form, which was approved by the Yonsei University Wonju Campus Human Studies Committees.

EMG data were collected using a Noraxon TeleMyo 2400T and analyzed using MyoResearch Master Edition 1.06 XP software (Noraxon Inc., Scottsdale, AZ, USA). Skin preparation of electrode sites involved shaving and cleaning with rubbing alcohol. Surface electrode pairs were positioned at an interelectrode distance of 2 cm. The reference electrode was placed on the ipsilateral clavicle. EMG data were collected for the infraspinatus muscle (4 cm below the spine of the scapula, on the lateral aspect over the infrascapular fossa of the scapula) (Cram et al., 1998). The raw signal was full wave rectified and filtered using a Lancosh FIR digital filter. The bandpass filter was used between 20 Hz and 300 Hz. The EMG data were processed

into the root mean square (RMS) value, which was calculated from 50-ms windows of data points.

The digital tension-meter using linear force measurement load cell (Noraxon Inc., Scottsdale, AZ, USA) was used to measure maximal force and 60%-maximal force (kg) in the infraspinatus muscle. The force data were collected using a Noraxon TeleMyo 2400T and MyoResearch Master Edition

1.06 XP software (Noraxon Inc., Scottsdale, AZ, USA). The target force to calculate 60%-MVIC (sub-MVIC) was determined based on the maximal force value using digital tension-meter. The sampling rate was 1000 Hz. The digital tension-meter was calibrated prior to each set of measurement (Figure 1).

Table 1

Characteristics of the subjects (N=12)

	Total	Male (n=8)	Female (n=4)	p
Body height (cm)	170.7 ± 7.3	174.9 ± 4.5	162.3 ± 2.1	0.00
Body mass (kg)	68.5 ± 15.5	76.6 ± 12.2	52.3 ± 1.7	0.03
Age (years)	26.0 ± 4.5	29.0 ± 3.1	21.3 ± 0.5	0.01

Figure 1

Testing Position:

A: MVIC-E (maximal voluntary isometric contraction with examiner`s resistance);

B: MVIC-DT (maximal voluntary isometric contraction with digital tension-meter);

C: Sub-MVIC (sub-maximal voluntary isometric contraction)).

Procedures

The dominant arm (the tendency to prefer a particular arm in performing selected tasks) was tested in all subjects (Yoshizaki et al., 2009). Recent findings have suggested that the determination of a dominant arm was based on hand-path kinematics and muscle activity in performing selected tasks (Bagesteiro and Sainburg, 2002). However, our study used a questionnaire to self-report arm dominance (ex. Daily-use dominant arm). Their self-reported dominant arms were right in all subjects.

Testing position required the subject to lay prone with the shoulder abducted at 90° and the elbow flexed to 90°, while the forearm in neutral position (Kendall and McCreary, 2005). Then, the subject moved to a position of shoulder external rotation to 90°. In a pilot study, isometric external rotation at 0° and 90° shoulder abduction were chosen because these positions are known to generate high levels of activity in the infraspinatus muscle (Kronberg et al., 1990; Jenp et al., 1996; Reinold et al., 2004). Standing or sitting external rotation at 0° and 90° shoulder abduction had a compensatory trunk motion compared to the prone position. Therefore, the prone position with the shoulder abducted at 90° was chosen. Additionally, the subject's elbow was fastened to the table using a non-elastic belt to prevent compensatory shoulder motion (Figure 1). Subjects were familiarized with each normalization trials during the 30 min period prior to testing. The familiarization period was completed when the subject was able to maintain three normalization methods for 5 s. All of the subjects were comfortable after the familiarization period, and none reported fatigue. A 15 min rest period was allowed after familiarization period before data collection began. The order of testing was randomized using random number generator (Microsoft Corp., Redmond, WA, USA), except for sub-MVIC. Sub-MVIC was calculated after MVIC-DT trial.

Three different testing methods were examined in this study (Figure 1). For the MVIC-E trial, subjects performed the maximal contraction of the dominant side arm by applying a manual resistance of an examiner to the subject's wrist. All subjects were given consistent verbal encouragement during maximal contraction. For the MVIC-DT trial, each subject performed a maximal contraction of the dominant side arm

using a wrist hanging handle. The handle was connected to the digital tension-meter. After MVIC-DT trial, a sub-MVIC value was calculated to 60% MVIC-DT force (Netto and Burnett, 2006). For the sub-MVIC trials, subjects were provided with visual feedback from a computer monitor that was positioned directly in the subject's line of sight to assist them in achieving the desired level of contraction. Each trial being performed incorrectly was stopped and repeated. If the subject performed the test incorrectly over 5 times, he or she was asked to rest 1 hour to prevent learning effects.

Physiological recovery was facilitated by allowing a 2 min recovery between normalization trials (Burnett et al., 2007). EMG activity was measured during each normalization trials for 5 s. The first and last second of the EMG data from each trial were discarded, and the remaining 3 s of data were used for further analysis (Reinold et al., 2004). An hour after the first session, the subject performed the second session following the identical protocol.

Statistical analysis

A repeated measure ANOVA was used to determine if there was systemic bias (for confirming the learning effects) between the first and second trial. Reliability of normalization methods in the infraspinatus muscle was calculated to determine the within-subject variation using two indices of reliability; ICC (3,1), the standard error of measurement (SEM). ICC values were calculated using the Statistical Package for Social Sciences, Version 12.0 (SPSS Inc, Chicago, IL). ICC is commonly used to assess test-retest reliability and reflects the relative reliability of a measurement. ICC >0.75 is considered excellent, 0.40–0.75 is regarded as fair to good, and 0–0.4 as poor (Crossley et al., 2004). To examine the consistency of the measurement, the SEM was calculated using Microsoft Excel [SEM = standard deviation*(1-ICC)^{1/2}]. Minimal detectable difference (95% confidence interval) (MDD₉₅) scores were calculated [MDD₉₅ = SEM × √2 × 1.96] (Ries et al., 2009). MDD₉₅ scores using a Microsoft Excel (set at a 5 % significance level) were calculated for the three normalization methods.

Results

There were no significant differences ($p > 0.05$) between the first and second test session in all of the normalization methods. These results indicated

that the learning effect did not occur between test sessions. The same day test-retest ICC scores, SEM, and MDD₉₅ for the EMG recordings from the infraspinatus muscle during each normalization test are documented in Table 2. The maximal and sub-MVIC force data using digital tension meter are presented in Table 3.

Discussion

The purpose of this study was to determine optimal normalization methods for the infraspinatus muscle in healthy subjects. The results of present study demonstrated that the sub-MVIC method has excellent test-retest reliability (ICC = 0.98) with a relatively small SEM (1.3 mV) and MDD₉₅ (3.5 mV), compared to MVIC-DT (ICC = 0.73; SEM = 6.3 mV; MDD₉₅: 17.3 mV) and MVIC-E (ICC = 0.42; SEM = 14.5 mV; MDD₉₅: 40.3 mV). Consistent with results of the present study, it has been previously reported that sub-MVIC methods were more reliable than MVIC in healthy controls when examining EMG data from biceps femoris and triceps muscles (Allison et al., 1993; Yang and Winter, 1983).

Several possible explanations exist for our results. First, providing visual bio-feedback at the reference point (60% MVIC torque) may have reduced the variability of measurement in the sub-MVIC method, compared with no visual feedback (MVIC-DT and MVIC-E). Previous studies suggested that providing visual feedback through monitor at the reference point markedly increased the reliability of the normalization method in the sub-MVIC (60% MVIC) (Burnett et al., 2007; Netto and Burnett, 2006). Second, the differences between

MVIC-DT and MVIC-E are influenced by methods of applying resistance. Although the same investigator applied manual resistance during the MVIC-E, the use of manual resistance is a potential source for variability (Dankerts et al., 2004). In contrast to MVIC-E, MVIC-DT is applied by fixed wrist hanging handle. During the measurement of MVIC, this method is useful for reducing variability introduced by the manual resistance method. Thus, MVIC-DT has higher reliability with a relatively small SEM and MDD₉₅ than MVIC-E.

Although MVIC is the most commonly used normalization technique, the MVIC may vary depending upon the sincerity, motivation or pain level of the individual. This variability may result in substantial MVIC variability and influence the interpretation of the EMG signal (Marras and Davis, 2001). Also, it is limited in application because it applies only to healthy subjects and requires substantial rest periods and thus, significant time. MVIC techniques would also have limited utility when evaluating individuals who are suffering from pain since they may not be willing to generate "true" MVICs (Baratta et al., 1998). Lund et al. (1991) reported that pain reduces maximal muscle activation, but has no influence on sub-maximal muscle activation in patients with musculoskeletal pain. Therefore, we suggest that sub-MVIC is appropriate for normalization during EMG studies, compared to MVIC. If MVIC for normalization is needed, MVIC-DT is more optimal than MVIC-E.

Table 2

Test-retest ICC scores, SEM, and MDD₉₅ among three methods.

	MVIC-E	MVIC-DT	Sub-MVIC
ICC	0.42	0.73	0.98
SEM	14.5 mV	6.3 mV	1.3 mV
MDD ₉₅	40.3 mV	17.3 mV	3.5 mV

ICC = intraclass correlation coefficient; MDD = minimal detectable difference;

SEM = standard error of measurement;

MVIC-E = maximal voluntary isometric contraction with examiner's resistance;

MVIC-DT = maximal voluntary isometric contraction with digital tension-meter;

Sub-MVIC = sub-maximal voluntary isometric contraction.

Table 3

The force data using a digital tension meter.

	MVIC-DT		Sub-MVIC	
	1 st trial	2 nd trial	1 st trial	2 nd trial
Force (kg)	56±14.9	54.1±15.4	32.4±8.2	32.3±8.5

*MVIC-DT = maximal voluntary isometric contraction with digital tension-meter;
Sub-MVIC = sub-maximal voluntary isometric contraction.*

The present study had some limitations. First, our results are not widely generalizable because all of our subjects were the healthy males. Thus, additional research is needed to establish whether our findings apply to subjects with shoulder pain as well as female subjects. Second, we did not measure between-day reliability. Between-days reliability becomes critical when assessing EMG parameters that are used as outcome measures (Elfving et al., 1999). However, it has been suggested that replacing the electrodes may be a major source of between-days test-retest variance, even if these are intended to be identically re-positioned (Veiersted,

1991). In conclusions, the present study demonstrated that sub-MVIC method using a providing visual bio-feedback at the reference point (60% MVIC torque) has excellent test-retest reliability in the infraspinatus muscle, compared to MVIC methods. This study also demonstrated that MVIC-DT is more reliable than MVIC-E. These findings provide evidence that sub-MVIC is more appropriate for comparing the EMG activity for the infraspinatus muscle as a normalization method. If MVIC for normalization is needed, MVIC-DT is more appropriate than MVIC-E.

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Anthropometric and Physical Fitness Differences Among Brazilian Adolescents who Practise Different Team Court Sports

by

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The objective of this work was to compare the anthropometric and physical fitness characteristics of Brazilian adolescents who practise team court sports and to compare specific parameters obtained for adolescents with data from the general population. This was a cross-sectional study of 1,348 male adolescents grouped as follows: basketball players (n = 287), indoor soccer players (n = 665), handball players (n = 108) and volleyball players (n = 288), all between 10 and 14 years of age. Anthropometric (body mass, body height, arm span, and body mass index) and physical fitness data (flexibility, muscular strength, explosive power, speed, aerobic fitness and agility) were collected. The Brazilian population was used as a reference and compared to the adolescent subjects using Z scores for all variables. Anthropometric characteristics and performances in physical fitness tests differed ($p < 0.05$) among players of different sports. In addition, for each variable assessed, adolescents who practised team court sports showed similar or improved results compared to their counterparts in the general population ($p < 0.05$). Furthermore, the anthropometric and physical fitness characteristics differed depending on the team court sport practised. These findings may elucidate which physical abilities are most impacted by the practise of a particular team sport as well as help teachers and physical education and sport professionals identify talented adolescents.

Key words: sports performance, cross-sectional studies, anthropometric and fitness variables, youth, team court sports.

Introduction

Team court sports are characterised by intermittent activities, in which intensive efforts are carried out over short time periods that alternate with periods of low intensity. This intermittent feature requires the use of all three energy systems (aerobic, lactic anaerobic and alactic anaerobic) to meet the players' metabolic demands. Moreover, these sports have complex demands that require a combination of individual skills, teamwork, technique, tactics and strategies, which contribute to the physical conditions of the players as well as the dynamic nature of team court sports, in general (Stone and Kilding, 2009).

In Brazil, the team court sports most practised by adolescents are basketball, indoor

soccer, handball and volleyball (Azevedo et al., 2007). Generally, such sports are practised in schools for recreational, social, competitive and other purposes.

Basketball has become one of the most popular court sports in many countries. Paiva Neto and Cesar (2005) performed a literature review on the physical abilities required to play basketball and defined it as a high-intensity sport with significant physical contact, high speed and constant jumps and shifts (both to attack and to defend). As a result, the main features of general physical fitness involved in basketball are anaerobic endurance and speed of movement. Other authors have added agility as a key factor in this sport (Ziv and Lidor, 2009).

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Indoor soccer is considered an indoor version of field soccer and is played with five athletes per team. The different types of displacement, including acceleration, kicking, passing, dribbling, tackling and jumping, likely resulting in significant neuromuscular adaptations that improve physical abilities such as agility, power, muscular strength and aerobic fitness (Alvarez et al., 2009; Castagna et al., 2007). Castagna et al. (2007) reported that, on average, adolescents who play indoor soccer reach maximal heart rates of $84\% \pm 5.4\%$ and peak oxygen uptake rates (VO_2) of $75\% \pm 11.2\%$ during a game.

Handball is a sport with great anaerobic demand. During the game, tasks such as pushing and blocking require high power and strength levels in the limbs and trunk regions (Gorostiaga et al., 2005; Izquierdo et al., 2002; Wallace and Cardinale, 1997). Gorostiaga et al. (2005) reported that stronger players with higher body mass have an advantage in handball because the requirements of the game, such as throwing the ball with power and speed, are met through jumping and physical contact with the opponent.

The characteristics of volleyball, including speed, jumping for spikes and blocks at high intensities over a short period of time result in fast and agile athletes who possess a high level of muscular strength and aerobic fitness (Gabbett et al., 2008). Adolescents are selected for this sport based on their skills, performance levels, physique and muscular strength (Benetti et al., 2005).

During adolescence, the impact of any sports discipline on anthropometric and physical fitness variables may be masked by hormonal changes caused by general physical growth (Silva and Cabral de Oliveira, 2010; Pearson et al., 2006). While team court sports have been widely researched, no studies have been conducted comparing data from young athletes with the general population. Moreover, the differences in anthropometric and physical fitness characteristics among adolescents who practise the four most widely practised court sports in Brazil are also unknown. The present extensive study may elucidate which physical characteristics are most impacted by participation in a particular team sport as well as assist teachers and physical education (PE) and sport professionals in identifying talented individuals.

Based on research in other countries and the characteristics specific to each sport discipline, the hypotheses of this study are as follows: 1) basketball and handball athletes have more muscle mass than players of other team court sports because there is greater contact between athletes in these sports disciplines; 2) youth subjects who practise basketball and volleyball have higher strength in the lower limbs because they jump more often than players of other sports; 3) indoor soccer athletes exhibit greater flexibility in the sit and reach test due to their higher mobilisation of back and posterior thigh joints, which are in constant use during matches; in addition, due to characteristics specific to indoor soccer, these athletes are faster and have better aerobic endurance than those of other sports; 4) youth team court athletes have better physical fitness results than their youth counterparts from the general population.

Thus, this study has the following objectives: 1) to compare the anthropometric and physical fitness characteristics across Brazilian adolescents who practise team court sports and 2) to compare specific variables (anthropometric and physical fitness characteristics) of adolescents who participate in team court sports with data from a matched general population.

Methods

For this cross-sectional study, data were extracted from the Brazil Sports Project (Projeto Esporte Brasil - PROESP-BR) from the National Secretariat for High-Performance Sports of the Ministry of Sports. More detailed information on the design and methodological aspects of the PROESP-BR have been previously published (Brazil Sports Project, 2007). The project was approved by the Ethics Committee on Human Research of the Federal University of Santa Catarina (UFSC), Florianópolis (SC), Brazil (Process number - 218/08).

The population studied consisted of male Brazilian students from 10 to 14 years of age enrolled in public and private schools. Sample selection was performed in a non-probabilistic intentional way; therefore, the PROESP-BR was disclosed and physical education teachers had the option of joining the project, assessing students and forwarding data to the PROESP-BR coordination.

During the 2004/2005 academic year, information on approximately 9032 male students (from 10 to 14 years of age) from 23 states of Brazil plus the Federal District was added to the PROESP-BR database. Data were collected in three states from the Midwestern Region ($n = 1354$), the Federal District ($n = 469$), eight states from the North-eastern Region ($n = 1484$), five states from the Northern region ($n = 925$), four states from the South-eastern region ($n = 3374$), and three states from the Southern Region ($n = 1426$). Of the students evaluated, 97.4% were studying in schools located in urban areas.

Participants in this study were required to fulfil the following inclusion criteria: 1) in-school participation (practising and competing) in basketball, handball, indoor soccer or volleyball for at least six months; 2) training sessions of at

least 50 minutes and 3) 3 or more days per week of sports practise. Information about the sports discipline, practise time, duration and weekly frequency was obtained from teachers and submitted the data to PROESP-BR.

Anthropometric measurements (body mass, body height and arm span) and physical fitness tests were obtained by PE teachers from each school who joined the PROESP-BR. All teachers were trained and had access to instructions for the application of tests and measurements through an internet site that included a video for standardisation and visual presentation of measurement techniques (Brazil Sports Project, 2007) prepared by members of the School of Physical Education, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil.

Table 1

The main physical components and the procedures used in each physical fitness test administered

Physical fitness test	Procedure
Sit-and-reach (flexibility)	The test evaluates flexibility. Subjects are seated with their legs joined and outstretched. The soles of their feet are supported in a standardised wood box (Well Box). Through inflection of their trunks, the subjects reach (with their ring fingers, arms joined and hands superposed) as far as they can toward/upon the box; they perform this reaching movement 2 times, and the maximal distance is recorded. The accuracy of this measurement in the present study is to within 0.1 cm.
1-min sit-ups (muscular endurance)	The test evaluates abdominal muscular endurance. Each subject is encouraged to do as many repetitions as they can in 1 minute ($n=1$).
Medicine-ball throw (power of upper limbs)	The test evaluates the power of the upper limbs. Each subject is seated with the backside of his trunk touching a wall. He then holds a medicine-ball with his hands (abreast of his chest) and throws it ahead as far as he can. He performs this action 2 times, and the maximal distance is recorded. The accuracy of this measurement in the present study is to within 0.1 cm.
Standing long-jump (power of lower limbs)	The test evaluates the power of the lower limbs. While standing, the subject propels himself by inflecting his knees jumping forward as far as he is capable. He performs this action 2 times, and the maximal distance is recorded. The accuracy of this measurement in the present study is to within 0.1 cm.
9-minute run (cardiorespiratory fitness)	The test evaluates cardio-respiratory fitness. Subjects run as far as they can in 9 minutes ($n = 1$). The accuracy of this measurement in the present study is to within 0.1 m.
20 m sprint (speed)	The test evaluates running speed. From a standing start, the subjects run for 20 metres. They do this 2 times, and the best time recorded. The accuracy of this measurement in the present study is to within 0.01 s.
4 m shuttle-run (agility and coordination)	The test evaluates agility and coordination. Subjects shift, as quickly as they are able, in a square area. They do this 2 times, and the best time is recorded. The accuracy of this measurement in the present study is to within 0.01 s.

Body mass was determined using a digital anthropometric scale calibrated from 0 to 150 kg with accuracy of 0.05 kg, and body height was measured using a portable stadiometer (fixed to the wall) calibrated from 0 to 200 cm with accuracy of 0.2 cm (Brazil Sports Project, 2007). For the measurement of body mass and height, adolescents removed their shoes and were instructed to wear a minimal amount of clothing (trunks and shirt). The body mass index (BMI) was calculated by dividing the body mass in kilograms by the squared height in metres. The arm span was determined by means of a tape measure (attached to the wall and parallel to the ground) with precision of 0.2 cm (Brazil Sports Project, 2007); the student was placed facing the wall for the measurement.

Standardisation and procedures for the physical fitness tests (flexibility, muscular strength, explosive power, speed, aerobic fitness and agility) were taken from the PROESP-BR (Brazil Sports Project, 2007) (Table 1).

Descriptive statistics regarding absolute and relative frequencies, mean values and confidence intervals were used to characterise the sample and physical tests performed. Data normality was verified and confirmed by the Kolmogorov-Smirnov test. The interaction between sport disciplines, anthropometric variables and physical fitness tests was verified. Since there was no interaction between variables ($p > 0.05$), analysis of covariance (ANCOVA) was used to compare the anthropometric variables and physical fitness tests of adolescents from the four types of sports, using age (controlled variable) as the co-variable. The Bonferroni multiple comparison test was used to identify differences between the four of sports.

To compare the anthropometric and physical fitness variables of adolescents in this study with reference populations, the Z scores of all variables were calculated using the formula: $Z = (X - M)/SD$, where Z = Z score, X = raw score of the variable, M = mean of the variable in the reference population and SD = standard deviation of the variable in the reference population. The Z score was adjusted for age by ANCOVA. The Brazilian population was used as the reference for body mass, height and BMI, according to data previously published in a Brazilian study that investigated adolescents from different regions

(Silva et al., 2010). The Brazilian population was also used as the reference for physical fitness tests, according to data reported by PROESP-BR (Brazil Sports Project, 2007). There are no data for Brazilian adolescents for variable arm span, which impairs the comparison of this study with the general population of young people in Brazil. The Bonferroni multiple comparison test and ANCOVA were applied at a significance level of 5%.

Results

Of the 9,032 records of male adolescents aged between 10 to 14 years, 1,348 adolescents were practising one of the four sports (basketball, handball, indoor soccer, or volleyball), and these individuals composed the study sample. The adolescents had an average age of 12.3 ± 1.3 years, and basketball, indoor soccer, handball and volleyball players had an average age of 12.4 ± 1.4 , 12.2 ± 1.3 , 12.5 ± 1.2 and 12.5 ± 1.3 years, respectively.

Most adolescents (49.3%) played indoor soccer, and a minority played handball (8.0%). Table 2 shows the sample distributions, mean values and confidence intervals for each anthropometric and physical fitness variable analysed.

Regarding the anthropometric variables (Table 3), adolescents who played indoor soccer were lighter than those who played other sports ($p < 0.01$), while adolescents who played basketball were taller than those who played other sports ($p < 0.01$). Adolescents who played indoor soccer had lower BMI values than those who played basketball and volleyball ($p < 0.01$). In addition, those who played basketball, handball and volleyball had greater arm spans than those who played indoor soccer ($p < 0.01$).

For the physical fitness tests (Table 3), those who played indoor soccer and volleyball had a better performances in the flexibility test than those who played basketball ($p < 0.01$). In the abdominal flexion test, basketball and indoor soccer players made more repetitions than volleyball players ($p < 0.01$). In the upper limb strength test, those who played basketball had better performances than those who played other sports ($p < 0.01$).

Table 2

Sample distribution(s) according to the sport discipline practised and descriptive values of anthropometric variables and physical fitness tests

Variables	n	%	(CI 95%)
<i>Total</i>	1348	100	
Basketball	287	21.3	(19.1 – 23.5)
Indoor soccer	665	49.3	(46.7 – 52.0)
Handball	108	8.0	(6.5 – 9.5)
Volleyball	288	21.4	(19.2 – 23.6)
	n	M	(CI 95%)
Age (years)	1348	12.3	(12.2 – 12.4)
Body mass (kg)	1348	46.3	(45.6 – 46.9)
Body height (cm)	1348	156.3	(155.6 – 157.0)
BMI (kg/m ²)	1348	18.6	(18.5 – 18.8)
Arm span (cm)	1346	159.6	(158.7 – 160.4)
Sit-and-reach test (cm)	1327	24.7	(24.2 – 25.2)
1-min sit-ups (repetitions)	1343	33.6	(33.1 – 34.0)
Medicine-ball throw (cm)	1342	316.0	(311 – 322)
Stationary long-jump (cm)	1345	160.7	(159.1 – 162.3)
9 min run test (m)	1229	1436.7	(1416.9 – 1456.4)
20 m run test (s)	1342	3.8	(3.7 – 3.9)
4 m shuttle-run (s)	1342	6.5	(6.4 – 6.5)

CI: confidence interval, M: mean, BMI: body mass index

Table 3

Analyses of covariance (co-variable = age) comparing mean values and confidence intervals of anthropometric variables and physical fitness according to sports discipline

	Basketball	Indoor soccer	Handball	Volleyball	F	p
Variable	M (CI 95%)	M (CI 95%)	M (CI 95%)	M (CI 95%)		
Body mass (kg)	50.0 (48.7-51.2)†	43.7 (42.9-44.5)	47.0 (45.0-49.0)†	47.9 (46.7-49.1)†	6.7	<0.01
Body height (cm)	159.5 (158.5-160.5)†‡§	154.2 (153.6-154.9)	156.3 (154.6-157.9)	157.2 (156.2-158.2)†	8.7	<0.01
BMI (kg/m ²)	19.3 (18.9-19.6)†	18.1 (17.8-18.3)	18.9 (18.3-19.5)	19.1 (18.7-19.4)†	13.1	<0.01
Arm span (cm)	163.5 (162.1-164.9)†	156.8 (155.8-157.6)	160.8 (158.4-163.1)†	161.2 (159.8-162.7)†	4.2	<0.01
Sit-and-reach test (cm)	22.2 (21.1-23.2)	25.6 (24.9-26.3)*	24.1 (22.3-25.7)	25.5 (24.4-26.5)*	11.3	<0.01
1-min sit-ups (repetitions)	33.8 (32.8-34.8)§	34.0 (33.3-34.6)§	33.2 (31.5-34.9)	31.8 (30.7-32.7)	10.2	<0.01
Medicine-ball throw (cm)	324.9 (317.8-331.9)†‡§	298.6 (294.5-302.6)	294.3 (284.2-304.4)	304.3 (296.7-311.8)	14.6	<0.01
Stationary long-jump (cm)	166.0 (163.1-168.9)†‡	157.9 (156.0-159.8)	157.0 (152.2-161.8)	162.5 (159.6-165.5)	2.6	0.04
9 min run test (m)	1374.4 (1332.9-1415.9)	1486.5 (1459.5-1513.5)*§	1430.0 (1358.6-1501.3)	1379.9 (1338.6-1421.1)	9.7	<0.01
20 m run test (s)	3.8 (3.7-3.8)§	3.8 (3.7-3.8)§	3.8 (3.7-3.9)	4.0 (3.9-4.0)	5.1	0.02
4 m shuttle-run (s)	6.5 (6.4-6.6)	6.4 (6.3-6.5)	6.6 (6.5-6.8)	6.5 (6.4-6.6)	1.8	0.14

M: Mean, CI: confidence interval, F: analysis of covariance value.* Significant difference compared to Basketball players ($p < 0.05$);

† Significant difference in relation to Indoor soccer players ($p < 0.05$);

‡ Significant difference in relation to Handball players ($p < 0.05$);§ Significant difference in relation to Volleyball players ($p < 0.05$)

Moreover, adolescents who played basketball had longer standing long jump results than those who played indoor soccer and handball ($p = 0.04$). Adolescents who played indoor soccer covered greater distances in the 9-minute run test than those who played basketball and volleyball ($p < 0.01$). The worst performances in the 20-m speed test were among those who played volleyball ($p = 0.02$). There were no significant differences in the performances of adolescents in the agility test ($p = 0.14$).

Comparing the Z scores of specific parameters (anthropometric and physical fitness characteristics) of adolescents with data from the reference population (Figure 1) revealed that young athletes had similar values (Z score = 0) or values that were better than the general population (Z score > 0). Teenage basketball players showed higher values of anthropometric variables (body mass, body height, BMI) and better performances on tests of flexibility, abdominal strength, and explosive power (of upper and lower limbs). In turn, adolescents who played indoor soccer performed better than the reference population in flexibility, abdominal

strength and aerobic fitness tests. Adolescents who played handball had higher body mass values and better performances in flexibility and abdominal strength tests. Adolescent volleyball players had higher values of anthropometric variables (body mass, body height, BMI) and better performances than the reference population on tests of flexibility and explosive power of upper limbs.

Discussion

The most recent studies related to team sports report a complexity of physical characteristics inherent to their practitioners, and one of the most important are anthropometric variables. In this study, basketball, handball and volleyball players showed higher body mass and arm span values compared to the general population and indoor soccer players. Generally, practitioners of sport disciplines that require jumping and throwing with the upper limbs are taller, heavier and larger (Bayios et al., 2006; Drinkwater et al., 2007; Withers et al., 1997; Ziv and Lidor, 2009). Bayios et al. (2006) compared the anthropometric characteristics and body

compositions of basketball and handball athletes, reporting that basketball players were taller than handball players. Withers et al. (1997) investigated the anthropometric characteristics of basketball, hockey and soccer players and found that basketball players were taller and heavier, thus presenting greater muscle mass, than players of other sports.

Information regarding the body height of the adolescents examined in this study should be interpreted with caution. Body height is not generally linked to sport specialisation and/or any sport in general because little or no change in body height can be accomplished through participation in sports. Moreover, not all adolescents in the present study preferred the same sports; some likely practised the only sports available at their school. Nonetheless, the authors of this study decided to keep body height as a descriptive variable in the analysis.

In this study, indoor soccer and volleyball players showed better performances in the flexibility test than basketball players. However, regardless of their sport disciplines, the performances of young athletes were, on average, 0.3 to 0.7 standard deviations above the mean reference population. In any sport, flexibility is essential for good performance. A possible explanation for the findings of this study is that flexibility is significantly affected by the movement autonomy to which the joint is regularly subjected (Erlandson et al., 2008). Young athletes exercise more than the general population, which can result in improved flexibility as well as other physical abilities. Moreover, the test employed in the present study requires flexibility in the dorsal and posterior thigh regions; thus, indoor soccer players, who use their legs constantly in the actions of the game, should rationally have an advantage.

In the abdominal strength test, basketball and indoor soccer players had better performance than those of other sport disciplines. Moreover, basketball, indoor soccer and handball players had 0.2, 0.3 and 0.2 standard deviations, respectively, above the collective performance score of the general population ($p < 0.05$). During puberty, muscle strength is directly proportional to body height, such that taller adolescents tend to have higher muscle strength (Oliveira and Gallagher, 1997); this may explain our findings

with regard to basketball players. Trainability is also expected to affect abdominal strength test results (Oliveira and Gallagher, 1997). Unlike volleyball, basketball, indoor soccer and handball require trunk mobility for the performance of dribbling; this difference in play may explain the similarity between volleyball players and the general population.

The literature reports that explosive power is an important feature for basketball players (Aşçi and Açıkada, 2007; Paiva and César, 2005). In the present study, adolescents who practised basketball had better results in tests pertaining to explosive power than those who played other sports as well as the reference population. Ackland et al. (1997) reported that, on average, a basketball athlete jumps 46 times per game; this action should enhance basketball players' performance scores when testing explosive power of the lower limbs.

In the present study, adolescents who played indoor soccer performed best in aerobic fitness tests compared to those who played other sports as well as the general population. Aerobic fitness is required for a player to perform well during an indoor soccer game because a high level of aerobic fitness decreases the probability of reaching fatigue (Alvarez et al., 2009; Castagna et al., 2009). Castagna et al. (2009) investigated the physiological demands during an indoor soccer game and reported high oxygen uptake rates and heart rates, indicating that aerobic fitness is a predominant requirement for success in indoor soccer. Alvarez et al. (2009) assessed the aerobic fitness of indoor soccer players at different competition levels and reported that these players had higher maximum oxygen uptake levels, better running economies and higher ventilatory thresholds than athletes who played other team sports at the same level.

The present study assessed the speed of the adolescents using the sprint test, which measures maximum speed that can be applied to any movement and depends on the development of agility, dynamic force, muscle elasticity, movement frequency and coordination as well as the domains of the movements employed. In the current study, basketball, indoor soccer and handball players performed better in this test compared to volleyball players. Sports such as indoor soccer, basketball and handball have

intermittent characteristics and employ sprint speeds during attack and counterattack actions in the games, whereas volleyball generally utilises reaction speed (Castagna et al., 2009; Gabbett and Georgieff, 2007).

The present study has the following limitations: 1) the physical fitness tests employed were not specific to the sport disciplines investigated; however, because the disciplines differ in their particular technical characteristics, motor tests used in a physical fitness battery to detect new talents, such as the PROESP-BR, can yield useful results for comparisons between sports; 2) the cross-sectional design used in this study does not allow for the determination of cause/effect relationships (i.e., whether the adolescents had the same physical fitness levels before practising particular sports); 3) this study does not consider the effects of biological maturation stages because this variable has been found to affect performance results in physical tests as well as the body compositions of adolescents (Bar-Or, 1995; Pearson et al., 2006); 4) the data used in this study were collected more than five years ago; however, the data were collected nationwide on adolescents from all regions of Brazil and provide the information required for comparison of athletes' results with those of the general population.

Notably the number of subjects studied for each sport differs widely because the study is part of a survey of the entire territory of Brazil. The distribution of subjects among the sports studied reflects the relative popularity of these sports in Brazil. Furthermore, the distribution found in this study is similar to previous published reports (Azevedo et al., 2007).

The present study is important for many reasons. First, the study employed data from all Brazilian regions, data that are difficult to obtain in a country with such diverse continental dimensions. Second the study included adolescents engaged in only one sports discipline at least three times per week, which greatly

diminishes (or eliminates) the potential effects of other sports on their physical abilities. Third, this is the first study in Brazil to compare the anthropometric characteristics and physical fitness of adolescents practising the four most popular team court sports in Brazilian schools. Finally, this study compared young athletes to the normal population, which is important because, during adolescence, young people undergo biological maturation that can influence physical performance. Thus, this study concludes that the practise of team sports makes young people more physically fit than the normal population.

Conclusions

Generalisation of the results of the present study is limited since the sample representativeness is low because schools that participated in the PROESP-BR did so voluntarily. Thus, the findings reported herein can only be interpreted in terms of the Brazilian adolescents from schools that participated in the project.

Compared to adolescents practising other sports, adolescents who played indoor soccer were lighter and had higher scores in flexibility, abdominal flexion, speed and aerobic fitness tests. Adolescents who played basketball were the tallest and had greater arm span, higher abdominal flexion, upper and lower limb strength and speed. Boys who played handball scored higher in the arm span test. Youth subjects who played volleyball scored higher in the arm span and flexibility tests. In addition, adolescents who practised team court sports performed better than the general population in all the tests/variables investigated (flexibility, abdominal flexion, upper and lower limb strength and aerobic fitness).

The present study is the first one to compare adolescents who practise team court sports with the general population. As such, it should help physical education and sports teachers to identify talents and to understand the physical variables most affected by the practise of these sports during adolescence.

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Temporal Activity in Particular Segments and Transitions in The Olympic Triathlon

by

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The Olympic Triathlon is a combined endurance sport. It includes back-to-back swimming, cycling, running and the transition between events (T1 & T2). The aim of the current study was to analyse the possible relationship between the Lost Time T1 & T2 and overall performance. The results showed that the percentages of total time corresponding to each part of the race were: 16.2% for swimming, 0.74% for the swimming-cycling transition (T1), 53.07% for cycling, 0.47% for the cycling-running transition (T2) and 29.5% for running. The correlations between each part of the race and the final placing were: $r=0.36$ for swimming, $r=0.25$ for T1, $r=0.62$ for the cycling, $r=0.33$ for T2, and $r=0.83$ for the running. Also, values of $r=0.34$ & $r=0.43$ were obtained for Lost Time T1 and Lost Time T2, respectively. In conclusion, losing less time during T2 has been demonstrated to be related to obtaining a better final result.

Key words: cycle-run transition, swim-bike transition, triathlon.

Introduction

The Olympic triathlon involves a 1.5 km swim, a 40 km cycle and a 10 km run completed under “draft-legal” conditions (Bentley et al., 2002). In order to be selected for the Olympics, the athletes must obtain an Olympic qualification ranking, via a competition system where points are obtained according to the placing in those races. The most common events used for this ranking are the ITU World Cups (Bentley et al., 2002).

Numerous studies have investigated the physiology of triathlon in laboratory-based conditions (Sleiver et al., 1996; Bentley et al., 2002, 2007a, 2007b; Hue et al., 1998, 2002; Millet et al., 2000, 2002). Currently, experiments are carried out to describe the physiological requirements of competition where external performance factors are considered (Cejuela et al., 2007; Vleck et al., 2008; Cala et al., 2009; Le Meur et al., 2011).

Triathlon represents an interesting model to examine differences in performance as the time differences can be analyzed for three different endurance disciplines.

Since 1981, elite male and female triathletes have improved their performances at the Hawaii Ironman Triathlon (Lepers, 2008). However, there are no studies describing the evolution of performance in Olympic-distance triathlon over the years.

Several studies have indicated a progressive reduction in speed, power output and heart rate during the event. The Olympic-distance triathlon requires a higher aerobic and anaerobic demands than constant-workload cycling exercises previously analyzed in laboratory conditions (i.e., time trial) or Ironman triathlons (Bernart et al., 2009; Le Meur et al., 2009).

Other studies analyzed the pacing-

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strategies of the triathletes during the running segment, showed that the first kilometers were run faster. This higher running speed may be due to the high pacing at what T2 (bike-run transition) is performed (Vleck et al., 2008; Le Meur et al., 2011).

The "Lost Time" for the swim-cycle (T1) and cycle-run (T2) transitions corresponds to the time difference between each competitor and the tri-athlete that started the bike (T1) or the run (T2) first (Cejuela et al., 2008). To the best of our knowledge, no study has analysed the possible relationship between the Lost Time T1 and T2 and the overall performance. Our hypothesis is that making the T2 faster, will improve the overall performance significantly.

Therefore, the aim of the present study was to analyse the temporal activity of the different segments and transitions of the triathlon over the years in international competitions (nine top-level Olympic-distance events) and relate it to the final performance in these competitions.

Material and Methods

Nine top-level men triathlon competitions held from 2000 to 2008 were studied: 6 World Championships (2000, 2001, 2004, 2006, 2007 and 2008) and 3 Olympic Games (2000, 2004 and 2008). The total number of participants was 537 ($n=537$), with 59.67 ± 11.08 (mean $\pm$ SD) participants per competition. All the tri-athletes who finished the race were considered for the analysis. We discarded the partial results of competitors who were disqualified or retired. All the participants gave their informed written consent to take part in this study that was conducted according to the Declaration of Helsinki. The Ethics and Research Committee of the Alicante University approved the study.

We gathered the data for all events in collaboration with the International Triathlon Union (ITU). In order to gather the times for all competitions we used the "ChampionChip®" microchip timing system. All athletes wore the chip on their left ankles during the races. When they crossed the reading mats, the partial times for each segment, transition and total competition times were recorded. These mats were placed at the start, entrance/exit to/from the transition area and at the finish line. The data at the 2002, 2003 and 2005 World Championships were not

analysed due to the fact that the timing system did not record the time taken to carry out the transitions separately (T1 & T2) but included them into the cycling time.

Determination of lost time in T1 and T2

Lost time in transitions T1 and T2 is the time lag between the first tri-athlete who starts cycling or running leaving the transition area, and the rest of the triathletes who arrived at the transition area in the same swimming or cycling pack.

This time depends on two factors. Firstly, the tri-athlete's position in the swimming or cycling pack when entering the transition area. The lower the rank is, the longer is the time lost during transition and vice versa. The higher the rank is, the less time is lost. Secondly, the time taken by the triathlete to carry out the specific actions required in the transition area, as changing equipment and crossing the designated area. This time is only valid as a reference for the swimming or cycling pack in which each triathlete reaches the transition area. It cannot be compared with other groups getting into the transition areas at different times.

The time lost in T1 and T2 can be calculated by filming and analysing the videos of each entrance and exit from the transition area (Cejuela et al., 2008) or by mathematical calculations based on partial times.

Lost time in T1 is calculated by the difference (in seconds) between the best partial accumulated time (at the end of T1) and the partial accumulated time of each tri-athlete belonging to the same swimming pack. The criteria used to decide whether two tri-athletes belong to the same pack is when the difference between them at the end of the swimming segment does not exceed 5 seconds.

Lost Time T1=Best partial accumulated time – accumulated time of each triathlete in the same swimming pack

Accumulated time=Time for the swimming segment + time for the swimming-cycling transition (T1)

Lost time in T2 is calculated by the difference (in seconds) between the best partial accumulated time (at the end of T2) and the partial accumulated time of each tri-athlete belonging to the same cycling pack. As in T1, the criteria used to decide whether two tri-athletes

belong to the same pack is when the difference between them at the end of the cycling segment does not exceed 5 seconds.

Lost Time T2=Best partial accumulated time – accumulated time of each triathlete in the same cycling pack

Accumulated time=Time for the swimming segment+Time for transition T1+Time for the cycling segment+Time for transition T2

The reason to set five seconds as the bench mark is based on results found in the literature. Hydrodynamic resistance calculations have shown that the ideal distance to draft behind another tri-athlete has not been exactly determined. However, it has been demonstrated that swimming more than five seconds behind the preceding tri-athlete does not provide any advantage over swimming alone (Chatard et al., 1998; Bentley et al., 2007).

Similar studies in cycling have shown that riding with practically inexistent separations between wheels can lead into 44% reduction in aerodynamic resistance, and up to 27% with a separation of two metres (McCole et al., 1990; Lucía et al., 2001; Faria et al., 2005). This is the main reason why five seconds have also been used as the bench mark in the cycling segment to consider whether two tri-athletes belong to the same pack.

Data analysis

Standard statistical methods were used to calculate mean, SD, and percentages. Time distribution was assessed via a general linear model with repeated-measures analysis of variance (ANOVA) to compare swimming, cycling, and running. Additionally, a Levene test for homogeneity of variances was completed on each dependent variable during the ANOVA, and, in each case, homogeneity of variance was found. Post hoc comparisons were completed using a Tukey HSD least significant difference. The T test was used to determine differences in T1 and T2. Pearson correlation coefficients were used to determine the relationships between each segment, transition and lost time T1 & T2 and the sport achievement. For all tests, the significance level was set at $p < 0.05$ and $p < 0.001$. The analyses were done using SPSS 15.0 (SPSS Inc. Chicago, IL). The coefficient of variation was used as a measure of intra-individual variation in time

distribution for each competition and total time spent during competitions and was calculated as the standard deviation of the difference between repeated measurements divided by the mean and multiplied by 100 (Atkinson and Nevill, 1998).

Results

Table 1 shows the mean ($\pm$ SD) time spent for each segment, transition and total time for all the competitions analysed. The mean total time spent by tri-athletes to finish the races was 1 hour, 52 minutes and 5 seconds $\pm$ 4 min. The longest segment was cycling, followed by running and swimming. T1 lasts longer than T2. T1 was the part of the race with the greatest variability.

Table 2 compares the average times of each part of the race of all the participants (swim: 18min 19s $\pm$ 25s, 6.89% CV (coefficient of variation); T1: 42s $\pm$ 16s, 33.83% CV; bike: 59min 9s $\pm$ 3min 41s, 6.73% CV; T2: 19s $\pm$ 7s, 27.17% CV; run: 33min 30s $\pm$ 44s, 5.68% CV; total time: 1h 52min 5s $\pm$ 4min, 4.58% CV) and the top 10 (swim: 18min 18s $\pm$ 25s, 2.47% CV; T1: 44s $\pm$ 15s, 37.12% CV; bike: 58min 48s $\pm$ 3min 27s, 5.68% CV; T2: 26s $\pm$ 7s, 31.4% CV; run: 31min 31s $\pm$ 43s, 2.64% CV; total time: 1h 49min 32s $\pm$ 3min 53s, 3.38% CV) with the values of the winners (swim: 18min 9s $\pm$ 25s, 2.26% CV; T1: 39s $\pm$ 15s, 38.92% CV; bike: 57min 56s $\pm$ 3min 20s, 5.76% CV; T2: 26s $\pm$ 9s, 35.56% CV; run: 31min 3s $\pm$ 51s, 2.71% CV; total time: 1h 48min 13s $\pm$ 3min 44s, 3.43% CV). Significant differences ($p < 0.05$) for the total time and for the running section were found (0.01).

There are significant differences between the mean time spent on T1 and T2 for all participants (43.74 $\pm$ 14.79s T1, T2: 28.65 $\pm$ 7.78s), the top 10 (40.07 $\pm$ 14.88s T1, T2 26.59 $\pm$ 8.35s) and winners (38.89 $\pm$ 15.14s T1, T2: 26 $\pm$ 9.25s). Therefore, no difference between groups was observed.

Table 3 shows the percentage of the total time (%) relative to each segment and transition. Cycling presents a higher value (52.73 $\pm$ 1.47%) than running (29.9 $\pm$ 0.72%) and swimming (16.35 $\pm$ 0.62%), while the transitions only account for 1.3 $\pm$ 0.33% of the total duration of the competition.

The percentages of the winners are very similar to the values obtained for the other competitors. Only the running segment showed significant differences (28.70 $\pm$ 0.58 winners; 29.14 $\pm$ 0.7 top 10; 29.90 $\pm$ 0.72 total) between the groups.

Table 1

*Mean ($\pm$ SD) time for each segment, transition and total time
in all the triathlon competitions analysed*

Competition	Swim	SD	CV	T1	SD	CV	Bike	SD	CV	T2	SD	CV	Run	SD	CV	Total Time	SD	CV
Sydney 2000 O.G	17min59s	24s	2.22	23s	3s	12.81	59min14s	1min27s	2.45	19s	2s	12.70	33min31s	1min57s	5.81	1h51min30s	2min41s	2.42
W.C 2000	18min28s	20s	1.85	46s	3s	7.41	1h1min19s	54s	1.46	34s	16s	20.96	32min57s	1min30s	4.51	1h54min6s	1min57s	1.73
W.C 2001	18min36s	32s	16.95	54s	3s	6.33	58min2s	1min56s	3.33	30s	4s	11.73	34min13s	1min57s	5.63	1h52min16s	3min46s	4.82
W.C 2004	18min30s	21s	10.87	1min7s	4s	6.60	52min19s	1min8s	2.31	37s	3s	7.80	32min35s	1min50s	7.91	1h45min6s	2min37s	3.50
Athens 2004 O.G	18min19s	20s	2.10	18s	1s	7.75	1h3min24s	2min21s	3.71	20s	2s	9.82	34min18s	1min52s	5.46	1h56min20s	3min42s	3.20
W.C 2006	17min51s	25s	2.70	51s	3s	6.46	1h4min13s	2min12s	3.43	35s	3s	9.24	33min32s	1min38s	4.89	1h57min	3min33s	3.04
W.C 2007	17min39s	14s	1.32	41s	4s	10.36	55min38s	1min11s	2.12	21s	3s	15.31	32min19s	1min36s	4.96	1h46min39s	2min22s	2.23
W.C 2008	19min1s	13s	1.16	46s	4s	7.84	59min19s	1min49s	3.10	24s	3s	11.02	34min13s	1min35s	4.65	1h53min43s	2min59s	2.63
Beijing 2008 O.G	18min23s	15s	1.35	28s	2s	6.15	58min52s	21s	0.59	30s	2s	7.60	33min49s	2min5s	6.18	1h52min1s	2min8s	1.91
Total Time	18min19s	25s	6.89	42s	16s	33.83	59min9s	3min41s	6.73	28s	7s	27.17	33min30s	44s	5.68	1h52min5s	4min	4.58

Mean in minutes and seconds. SD=in seconds. CV=coefficient of variation in %.

Table 2

*Comparison of the mean times in each part of the race between all the competitors,
top 10 and the winners in all the triathlon races analysed*

	Swim	Cycle	Run	M (95% IC)	p
Total (N=538)	1103.2 $\pm$ 75.9	3531.1 $\pm$ 237.7		-2427.7 (-2450.4 to -2405.1)	0.001
	1103.2 $\pm$ 75.9		2007.2 $\pm$ 113.9	-904.1 (-926.6 to -881.3)	0.001
		3531.1 $\pm$ 237.7	2007.2 $\pm$ 113.9	-1523.7 (-1546.4 to -1501.1)	0.001
Top ten (N=87)	1088.8 $\pm$ 26.8	3490.1 $\pm$ 198.2		-2401.1 (-2443.7 to -2358.6)	0.001
	1088.8 $\pm$ 26.8		1888.6 $\pm$ 49.9	-799.7 (-842.2 to -757.1)	0.001
		3490.1 $\pm$ 198.2	1888.6 $\pm$ 49.9	-1601.4 (-1644.1 to -1558.9)	0.001
Winners (N=9)	1088.8 $\pm$ 24.6	3476.1 $\pm$ 2.2		-2387.1 (-2528.4 to -2245.7)	0.001
	1088.8 $\pm$ 24.6		1862.8 $\pm$ 50.5	-774.1 (-915.3 to -632.6)	0.001
		3476.1 $\pm$ 2.2	1862.8 $\pm$ 50.5	-1613.1 (-1754.4 to -1471.7)	0.001

Values expressed as mean (M) $\pm$ SD and 95% CI. p values of analysis of variance comparing differences between groups.

Table 3

*Comparison of the mean times in each part of the race between all the competitors,
top 10, and the winners in all the triathlon races analysed*

	Total (538)	TopTen (87)	Winners (9)	M (95% IC)	p
Swim	1103.2 $\pm$ 75.9	1088.8 $\pm$ 26.8		14.3 (-4.8 to 33.6)	0.186
	1103.2 $\pm$ 75.9		1088.8 $\pm$ 24.6	14.3 (-41.6 to 70.2)	0.819
		1088.8 $\pm$ 26.8	1088.8 $\pm$ 24.6	-0.03 (-58.3 to 58.2)	1.000
Cycle	3531.1 $\pm$ 237.7	3490.1 $\pm$ 198.2		40.9 (-22.1 to 104.1)	0.279
	3531.1 $\pm$ 237.7		3476.1 $\pm$ 200.2	55.1 (-128.4 to 238.4)	0.761
		3490.1 $\pm$ 198.2	3476.1 $\pm$ 200.2	14.1 (-177.1 to 205.1)	0.984
Run	2007.2 $\pm$ 113.9	1888.6 $\pm$ 49.9		118.6 (89.6 to 147.6)	0.001
	2007.2 $\pm$ 113.9		1862.8 $\pm$ 50.5	144.3 (59.9 to 228.7)	0.001
		1888.6 $\pm$ 49.9	1862.8 $\pm$ 50.5	25.7 (-62.2 to 113.6)	0.771

Values expressed as mean (M) $\pm$ SD and 95% CI. p values of analysis of variance comparing differences between groups.

Figure 1

The mean of the Pearson correlation coefficients obtained ($p < 0.001$) between each segment, transition and lost time T1 & T2 and the final classification of a triathlon competition

In order to see whether the time distribution within the race had any relationship with the overall performance, correlations between each part of the race (including lost time in T1 & T2) and the final classification were calculated. The results are shown in Figure 1. The running segment presented a higher correlation (0.82), followed by cycling (0.62) and Lost Time T2 (0.43).

Discussion

The time lost in T2 showed a correlation of 0.43 with the overall performance of the tri-athletes in competition. This value was even higher than the ones presented by the other two transitions (T1 & T2) and the swimming segment. Losing less time is related to obtaining a better final result. It is a performance factor that should be taken into account when analysing top-level Olympic Triathlon competitions. This new variable varies from 1 to 15 s. It represents a small percentage of a race that lasts slightly less than 2 hours, but it can make a big difference in the final result as the leading positions are often decided by final sprints with differences of a few seconds. Therefore, this time may be a decisive factor regarding the final classification in a

triathlon race.

The time lost in T2 is a valid determinant of the final performance of tri-athletes arriving at T2 in the same cycling pack. It depends on two factors: firstly, arriving at T2 in the most advanced position possible within the pack, and secondly, carrying out the necessary actions in T2 as quickly as possible. Some studies tried to identify the changes in speed at decisive points during the competition using a GPS device for each athlete and several video cameras (Vleck et al., 2007). High correlations were found between the speed and position at the start of the swimming (-0.88 for men, -0.97 for women), cycling (0.81 for men, 0.93 for women) and running (-0.94 for men, -0.71 for women). These changes in speed at the beginning and at the end of the segments, together with the transitions, seem to be important factors that may decide the final result. These changes in speed at the start/end of the transitions can be the main reason that could explain the time lost in T1 and T2.

The Olympic Triathlon is a complex sport, not only because three different disciplines are performed back-to-back without stopping the clock, but also because of the speed and precision required during the transitions to pass from one

segment to the next (Millet and Vleck, 2000). Transitions are a fundamental part of a triathlon race as they can determine the final results in many competitions. This study takes another step forward in analysing Olympic Triathlon performance as we divided the competition into the following segments: swimming, swimming-cycling transition (T1), time lost in T1, cycling, cycling-running transition (T2), time lost in T2, and running.

The swimming segment showed a low correlation with the final position at the end of the race. This finding is slightly different to the ones obtained in other studies. Landers (2002) analysed 10 international ITU competitions and the correlation of the swimming segment with the overall performance was higher (0.49 versus 0.36). This may be due to the increase in the level of male swimming performance over the last years. It seems the differences in this segment used to be bigger and more decisive in the past than in current competitions. It is very important to be placed in a good position at the end of the swim part, in order to be able to make the first group in the cycling segment (Millet and Veck, 2000). Drafting is also important to consider when covering this segment, in order to save as much energy as possible for the rest of the race (Chatard et al., 1998; Millet et al., 2002). Despite the fact of a low-medium correlation found in the swim, swimming slower does not allow you to compete at the front of the race in further stages of competition. The level of swimming is very high in international elite Olympic Triathlon and a very numerous main pack is formed in the lead whose members present a similar swim speed. This means that the tri-athletes who are not part of the front pack will find it very difficult trying to win the competition.

A low correlation was found between the first transition (T1) and the overall performance. During the cycling segment it is possible to make up the time lost in T1 by catching up with the pack. This could be the reason that would explain the low value found for this correlation. The profiles of most championship routes do not have difficult mountainous sections (steep hills or mountain passes), except for the 2004 Olympic Games, although they do have certain technical difficulties (sharp bends, narrow sections, etc.). Therefore, drafting may be a beneficial tactic in

swimming and cycling to increase elite Olympic triathlon performance (Bentley et al., 2007).

The Lost Time in T1 is different for each swimming pack. We identified two packs in our analysis; 1st and 2nd swimming packs when exiting the water. The mean correlations of the 1st and the 2nd swimming pack with the final position at the end of the race were 0.34 and 0.4, respectively. Again, the reason of these medium-low correlations could be the flat routes presented by the cycling sections, where the tri-athletes can make up the time lost in the transition easier.

During the cycling segment in elite triathlon competitions with flat profiles, one or two (three at the most) packs are formed. Normally, those who are not part of the first pack cannot expect to win. This is shown by the medium-high correlation obtained between the cycling segment and the final classification. This result reinforces the hypothesis of the importance of the tactics during this part of the race (Bentley et al., 2007). Significant differences were found in the correlations between the time taken to complete the cycling segment and the overall performance in the different competitions analysed. These differences may be due to two reasons. Firstly, the individual or group tactics adopted by the tri-athletes (aggressive or conservative: trying to break away from the main pack to reach the running segment with a time advantage, or trying to save as much energy as possible to reach the running segment in the best possible condition). And secondly, the orography of the segment (if the profile has mountainous difficulties, the correlation is higher than if the profile is flat). Also, with flat profiles, it is easier and more beneficial to draft in a pack than when riders have to climb mountains, passes or steep slopes (Faria et al., 2005). In this case, the race leads to the creation of smaller packs as was the case in the 2004 Olympic Games. This was the only competition where the correlation between the cycling segment and the final classification was higher (0.86 ± 0.12) than the correlation obtained for the running part (0.76 ± 0.15).

The second transition (cycling-running or T2) has been described as the most important with regard to the final result of the competition (Millet and Veck, 2000). However, we found a low correlation between the time taken for T2 and the final classification. Carrying out a good T2 determines

the time lost in T2, which showed a higher correlation with the final result. The running segment has been described as the most decisive segment regarding the performance in triathlon (Sleivert and Rowlands, 1996; Hue et al., 2002; Bentley et al., 2007). In the present study, we obtained the highest correlation with the final classification of all the segments and transitions. This finding reaffirms the data found in the literature. Also, the tactics adopted in the cycling segment will affect the correlation between the running part and the overall performance.

Two different race scenarios that could cause differences were identified. The first one, when the profile of the cycling segment has major orographic difficulties. The 2004 Olympic Games race was the only one that showed a higher correlation for the cycling segment than for the running segment. This was probably due to the fact that the cycling segment was performed over a mountainous profile. The second one, when aggressive tactics leading into breakaways are adopted during the cycling segment. This was the case in the 2006 World Championships, and the correlation between the cycling segment and the overall performance was similar to the one obtained for the running part (0.82 vs. 0.83).

Anthropometry is another factor that may influence performance in the triathlon. The study by Knechtle et al. (2010), related to race time Ironman triathletes anthropometry, found greater relations with the segment of cycling and running, than with swimming. Just as the effects on the recovery phase between competitions, which have been studied in triple ironman triathlon by Knechtle et al. (2009).

According to the competitions analysed, it seems that the tactics adopted by the male triathletes during the cycling segment tend to be conservative. Also, it could be that it is more difficult to create circumstances where breakaways reach the running segment with a clear advantage. In addition, the performance level in the cycling segment may be very similar for all the participants, and the fact that there is little collaboration or teamwork may be the reason why breakaways rarely happen. New studies analysing trends during the cycling part in the current format of the World Championship Trial Series competition are needed for further understanding.

Determining the duration of each part of the race (swimming, T1, cycling, T2 & running) was the second aim of the present study. The results show that the average total time found for the men's Olympic Triathlon competition is similar to the values obtained by other investigations (Landers, 2002). Also, highly significant differences were found for the swimming segment between the present study and the previous ones. Faster swim times were obtained this time, so it seems that the current swim performance is higher nowadays. The average time to complete the cycling segment was similar to the ones reported by other studies. However, the references in the literature analysed events where drafting during cycling was not allowed, so this segment could cause greater fatigue prior to the running segment (Paton and Hopkins, 2005). Finally, the average times for the running segment did not show significant differences.

Comparisons between male winners and all participants were carried out. The results showed highly significant differences for the running time, and significant differences for the total duration of the race (Table 3). As it occurred with absolute times, the running segment showed the greatest difference between the winners and the rest of the participants, indicating that the performance in this segment has a greater impact on the final result. Considering the fact that the swimming/cycling segments offer the possibility of swimming/riding in a pack, and that the level of the participants are very similar, the time differences appear in the last segment. Running in a group has less biomechanical and physiological effects than in the other two segments, and the preceding fatigue has a very significant influence. These findings represent an important difference with the other triathlon modalities where drafting is not allowed during the cycling (e.g. the Ironman). Therefore, the analysis of the competition and final performance factors are different from the Olympic-distance Triathlon competition (Paton and Hopkins, 2005; Bentley et al., 2007).

Conclusions

Losing less time during T2 has been demonstrated to be related to obtaining a better placing at the end of an Olympic-distance

triathlon. Lost Time T2 varies from 1 to 15 s and it represents a small percentage of the race, but it can make a big difference in the final result, as the leading positions are often decided by final sprints with differences of a few seconds.

Competitors need to leave the water in the leading pack to have better chances of

winning. The time lost in T1 can be made up in the initial kilometres of the cycling segment, with a medium-low ($p < 0.05$) significance regarding the final placing. The orography of the cycling section and any breakaways can lead to differences in the importance of the time lost in T2. The tactics adopted in the cycling segment may affect the correlation between the running and the final result, which showed the highest values overall.

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Offensive Sequences in Youth Soccer: Effects of Experience and Small-Sided Games

by

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The present study aimed to analyze the interaction and main effects of deliberate practice experience and small-sided game format (3 vs. 3 and 6 vs. 6 plus goalkeepers) on the offensive performance of young soccer players. Twenty-eight U-15 male players were divided into 2 groups according to their deliberate practice experience in soccer (i.e., years of experience in federation soccer): Non-Experienced (age: 12.84 ± 0.63 years) and Experienced (age: 12.91 ± 0.59 years; experience: 3.93 ± 1.00 years). The experimental protocol consisted of 3 independent sessions separated by one-week intervals. In each session both groups performed each small-sided game during 10 minutes interspersed with 5 minutes of passive recovery. To characterize the recorded offensive sequences we used the Offensive Sequences Characterization System, which includes performance indicators previously applied in other studies. No interaction effects on the offensive performance were found between both factors. Non-parametric MANOVA revealed that the factor “experience level” had a significant effect ($p < 0.05$) on performance indicators that characterize the development of offensive sequences, especially in 6 vs. 6 + GKs. While experienced players produced longer offensive sequences with greater ball circulation between them, the non-experienced participants performed faster offensive sequences with a predominance of individual actions. Furthermore, significant differences were observed ($p < 0.05$) in the development and finalization of offensive sequences within each group, when comparing small-sided game formats. Evidence supports that small-sided games can serve several purposes as specific means of training. However, the manipulation of game format should always consider the players’ individual constraints.

Key words: association football, constraints-led approach, performance, skill acquisition.

Introduction

In the scope of constraint-led approach, sport performance and skill acquisition emerge from the interaction of constraints pertained to the players, the task and the environment (Handford et al., 1997; Davids et al., 2005; Williams and Hodges, 2005). There have been several attempts to explain how the manipulation of practice constraints influences physical conditioning and/or sport performance (Hill-Haas et al., 2011; Dellal et al., 2011a), however, none of these studies tried to analyze the interaction effects between individual and task constraints on the development of expertise in soccer.

The individual constraints refer to intrinsic characteristics of a person, such as body morphology, chronological and biological age, fitness, skill or experience levels, perceptual and cognitive development, and others (Williams and Hodges, 2005). These unique features play a relevant role in the way a player interacts with external constraints in a specific performance context (Davids et al., 2006). Some studies sustain that capacities and knowledge of skilled players are essentially related to the time spent on training and quality of sport-specific practice, rather than to the maturation process (Ward and Williams, 2003; Vaeyens et al., 2007; Ford and

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Williams, 2012). One of these works was developed by Helsen et al. (1998), who examined the historical practice profiles of professional, semi-professional and amateur soccer players. These authors concluded that the amount of time spent on collective training was the factor that most distinguished the three skill levels. In a recent review, Ericsson (2006) suggested that the effects of mere experience differ greatly from those of deliberate practice (i.e., activities specifically designed to improve performance). We can assume that the time spent on these types of activities, which can be defined as deliberate practice experience, can be an important component of youth soccer developmental programs. As children gain experience with age and exposure to the sport, they probably develop and refine specific structures of knowledge and motor skills that make them technically and tactically more competent in their game performance.

On the other hand, at present, the researchers take more of an interest in the use of small-sided games (SSGs) in training. Previous studies have pointed out that SSGs are an efficient strategy to increase players' specific practice time, and to improve physical capacities and technical skills within a major tactical involvement (Reilly, 2005; Duarte et al., 2009). Regardless of their age or skill/experience level, participants of the various studies reviewed performed a greater number of ball possessions, ball touches, dribbles, passes, shots, goals, tackles, interceptions, ball recoveries, and "off-the-ball" movements, when exposed to smaller game situations (Capranica et al., 2001; Jones and Drust, 2007; Hill-Haas et al., 2009; Duarte et al., 2009; Katis and Kellis, 2009; Kelly and Drust, 2009; Casamichana and Castellano, 2010). Hence, the game format presented to players constrains them to solve specific game problems with implications on the individual and collective actions that are performed (Davids et al., 2005; Dellal et al., 2011b; Almeida et al., 2012). Nevertheless, it is not clear how players with different levels of experience respond to similar practice tasks. Are there important differences in their offensive performance?

Given the world-wide popularity of soccer compared to other team sports, there is a surprising lack of scientific interest in

the relationship between the deliberate practice experience and the manipulation of task constraints in the development of game actions (for an exception see Ford and Williams, 2012). Therefore, to better understand the attacking playing patterns emerging during SSGs performance, this study aimed to analyze the interaction and main effects of both deliberate practice experience and SSG format on performance indicators that characterize the offensive sequences produced by teams of young soccer players.

Material and Methods

Participants

Twenty-eight U-15 males were selected as participants. Ethics approval for this study was granted by the researchers' faculty scientific board and parental written consent was received prior to all experimental procedures. Participants were divided into 2 groups according to their deliberate practice experience in soccer; a questionnaire was applied to determine the years of experience in soccer. The Non-Experienced group (N-Exp) consisted of 14 participants (age: 12.84 ± 0.63 years) selected from physical education classes with no deliberate practice experience in soccer. The Experienced group (Exp) was formed by 14 participants (age: 12.91 ± 0.59 years) selected from a U-15 club team competing at the Portuguese regional level and with 3.93 ± 1.00 years of deliberate practice experience in soccer. Each group was divided into 2 balanced teams in the 6 vs. 6 + GKs games: 1 goalkeeper, 2 defenders, 3 midfielders and 1 forward. In the 3 vs. 3 + GKs games, the same goalkeeper, one of the defenders, one of the midfielders and the forward took part in the experiment; the defender and the midfielder were randomly selected. Matches were always contested by teams with the same experience level.

Procedures

Both groups completed 3 independent sessions separated by one-week intervals. All matches were played in the afternoon, during the same hours of the day (between 3:00 and 5:00 p.m.), and under mild temperatures. In each session both groups performed the 2 SSGs – 3 vs. 3 + GKs (4-a-side) and 6 vs. 6 + GKs (7-a-side) – during periods of 10 minutes interspersed with 5 minutes of passive recovery. Matches were

divided into two 5-min halves with 1-min intervals for midfield exchange. Game duration was based on coach experience, taking into account that each 5-min half does not correspond to the effective playing time due to the stoppages (e.g., fouls, goals, throw-ins, goal kicks, etc.) that normally occur in soccer matches (Casamichana and Castellano, 2010). Time procedures employed in previous research concerning SSGs in soccer and futsal were also considered (Jones and Drust, 2007; Duarte et al., 2009; Casamichana and Castellano, 2010; Almeida et al., 2012).

The total number of SSGs performed was 12 (i.e., 3 of 3 vs. 3 + GKs and 3 of 6 vs. 6 + GKs games per group), and they were presented in a random order in each session. Whereas the 3 vs. 3 + GKs game is frequently employed in training in youth soccer, the 6 vs. 6 + GKs game is an official competitive game format used in younger age categories across several countries. In the present study, these SSGs were played in pitches with 46 x 31 m and 62 x 40.4 m (length x width), respectively. The relative space available for each player (ratio of pitch area per player), and the dimensions of goalkeeper areas (9 x 24 m; length x width) were similar in both game situations. Prior to game practice, participants performed a 10-min standardized warm-up. Game situations were explained before the first session and participants were asked to play at their best level in order to succeed in SSGs. All the official rules of soccer were implemented apart from the offside rule.

The research took place in a sports park equipped with artificial turf, having all the necessary conditions for soccer practice. Two 7-a-side goals were used with the official dimensions of 6 x 2 m, 12 5-size balls properly prepared for the matches, as well as game shirts to differentiate teams. The match time was clocked continuously with a watch (Nike WR0066-001 Triax, Nike® Inc., U.S.A.); one assistant was placed in each touchline of the pitch to reduce the time loss when the ball went out of play. Refereeing was carried out by a neutral assistant. The experimental sessions were only held if the pitch surface was perfectly dry. There was no audience and assistants were not allowed to concede any instructions or feedbacks during practice.

Data Collection and Analysis

Data were always collected with a digital video camera (Sony DCR-SR77, Sony®

Corporation, China) set up on a tripod 42 m from the closest corner of the larger pitch, and at an elevation of 15 m. The camera remained fixed on the tripod, after obtaining a clear and comprehensive plan of the entire pitch surface in each SSG. Data were recorded on a Microsoft Office Excel 2007 sheet (Microsoft® Corporation, U.S.A.) and, finally, exported to the SPSS Statistics, version 17.0 (SPSS® Inc., U.S.A.).

The units of analysis were the offensive sequences, which were understood as the execution of one or more individual and/or collective tactical-technical actions, defined according to criteria of the beginning and end of ball possession. The characterization of each offensive sequence was carried out through a hand notation analysis system specifically designed for this purpose – Offensive Sequences Characterization System (OSCS) – and includes performance indicators previously applied in other investigations. Thus, the offensive sequences were characterized in terms of Duration of ball possession (Hughes and Churchill, 2005; Almeida et al., 2012), number of Players involved (Almeida et al., 2012), number of Ball Touches (Dellal et al., 2011b; Almeida et al., 2012), number of Passes (Hughes and Bartlett, 2002; Hughes and Franks, 2005; Redwood-Brown, 2008), number of Shots (Hughes and Bartlett, 2002; Hughes and Franks, 2005; Almeida et al., 2012), and Result of the Offensive Sequence (Almeida et al., 2012). This last performance indicator is a nominal variable and assumes one of three forms: i) *total success*: goal scored; ii) *partial success*: shot on goal without scoring, the ball hits the goalposts/crossbar or is saved by the goalkeeper or another player near the goal line; iii) *unsuccessful*: shot goes wide of the goal, shot intercepted by an opponent, and loss of ball possession. Since these performance indicators directly derived from the behaviors observed through the system, they are from now on designated as simple indicators.

Moreover, the comparison of performances between teams or team members is often facilitated if the performance indicators are expressed as ratios (Hughes and Bartlett, 2002). Thus, we also analyzed composite indicators, which were obtained by dividing 2 simple indicators: Players involved/Duration (of ball possession), Ball Touches/Duration,

Passes/Duration, Ball Touches/Players involved, Passes/Players involved, Passes/Ball Touches, and Goal/Shots. Additionally, the simple and composite indicators were grouped in 1 of the 2 levels configured to characterize the offensive sequences: development and finalization.

Reliability

Prior to the study, an observation protocol was completed in order to determine the intra-operator reliability when collecting data with the OSCS. The protocol included 2 analysis sessions spaced at least 7 days apart to prevent any learning effects influencing the data (Jones and Drust, 2007). In both sessions (test and retest), data corresponding to 20% of the total images' sample (80 offensive sequences) were observed and notated. First, the level of agreement for simple performance indicators was determined using the number of exact agreements observed between each of the 2 analysis sessions. The percentage agreement between test and retest measures provides an indication of the consistency of the data (Kelly and Drust, 2009). Results showed high percentages in all performance indicators analyzed (from 85 to 100%). Then, this approach was supplemented by the calculation of the weighted version of kappa statistic to evaluate the reliability of both assessments in all performance indicators (Robinson and O'Donoghue, 2007). There was a very good strength of agreement (O'Donoghue, 2010), since kappa values (κ) ranged from 0.84 to 1.0; these results testify the intra-operator reliability in using the system.

Statistical Analysis

The effects of the "experience level" and "SSG format" on offensive performance indicators were primarily studied through descriptive statistics (means, standard deviations, and absolute frequencies). Then, after the rejection of the multivariate normality assumption (using Kolmogorov-Smirnov tests for each performance indicator) and the homogeneity of covariance matrices (using Box's M test), non-parametric MANOVAs were applied to assess the interaction and the main effects of both factors on simple and composite indicators. For each MANOVA, partials eta squared (η_p^2) were calculated as measures of effect size. As a third step, if the effects of factors on performance indicators were

significant, it would be essential to identify in which the significant differences occurred. Multiple Mann-Whitney tests were applied for that purpose. Finally, chi-square tests were selected for the nominal variable of the Result of the Offensive Sequences. For all statistical procedures alpha (α) was set at 0.05.

Results

In the 12 matches played, an overall of 398 offensive sequences were identified. Table 1 presents the descriptive statistics (mean $\pm$ SD) of performance indicators that characterize the offensive sequences produced by players in each SSG.

First of all, the MANOVA models revealed that the interaction effects of both factors (experience level*SSG format) were not significant on simple and composite performance indicators ($p=0.72$; $\eta_p^2=0.007$, and $p=0.423$; $\eta_p^2=0.015$, respectively). When considering the main effect of the "experience level" in 3 vs. 3 + GKs games, the non-parametric MANOVAs demonstrated significant effect on simple and composite indicators that characterize the offensive sequences ($p<0.001$; $\eta_p^2=0.106$, and $p<0.001$; $\eta_p^2=0.108$, respectively). Concerning the development of offensive sequences, Mann-Whitney tests exhibited significant differences between groups (N-Exp vs. Exp) in number of: Players involved ($p=0.003$), Passes ($p<0.001$), Passes/Duration of ball possession ($p=0.005$), Passes/Players involved ($p<0.001$), and Passes/Ball Touches ($p<0.001$). No differences between experience levels were observed in performance indicators associated to the finalization of offensive sequences.

The application of non-parametric MANOVAs testified that the deliberate practice experience showed a significant effect on simple and composite performance indicators underlying the characterization of offensive sequences in 6 vs. 6 + GKs games ($p=0.012$; $\eta_p^2=0.081$, and $p=0.024$; $\eta_p^2=0.07$, respectively). The Mann-Whitney test revealed that the offensive sequences differed significantly between both groups in the performance indicators such as Duration of ball possession ($p=0.016$), Players involved ($p=0.004$), Ball Touches ($p=0.003$), Passes ($p<0.001$), Passes/Duration ($p=0.009$), Passes/Players involved ($p<0.001$), and Passes/Ball Touches

($p=0.008$). No significant differences were observed at the finalization level in any of the performance indicators analyzed.

The factor “SSG format” evidenced a significant influence on simple and composite indicators of the offensive sequences produced by the “N-Exp” group ($p<0.001$; $\eta_p^2=0.151$, and $p<0.001$; $\eta_p^2=0.062$, respectively). Significant differences were discriminated between SSGs in the following performance indicators: Players involved ($p=0.003$), Ball Touches/Duration ($p=0.003$), Ball Touches/Players involved ($p=0.005$), and Shots ($p=0.02$). Regarding the “Exp” group, the non-parametric MANOVA reported a significant effect of the factor “SSG format” only on simple indicators ($p<0.001$; $\eta_p^2=0.194$). Therefore, the differences between

game formats in the “Exp” group were only significant for the Duration of ball possession ($p=0.033$), Players involved ($p<0.001$), and Shots ($p=0.011$).

Table 2 demonstrates a broader perspective on the offensive sequences’ finalization in both experience levels and in each game format.

The statistical inference showed that the distribution of the offensive sequences’ results was homogeneous between groups for 3 vs. 3 + GKs ($p=0.478$) and 6 vs. 6 + GKs ($p=0.236$) games. According to an intra-group perspective, statistical evidence indicated that the distribution of the results for this category was not homogeneous in both SSGs for the N-Exp group ($p=0.04$), although it was homogeneous for the Exp group ($p=0.734$).

Table 1

Mean values ($\pm$ SD) of performance indicators that characterize the offensive sequences produced by groups in each SSG format.

Performance Indicators	3 vs. 3 + GKs		6 vs. 6 + GKs	
	N-Exp	Exp	N-Exp	Exp
DEVELOPMENT				
Duration of ball possession (s)	10.67 (6.53)	12.39 (7.94)†	12.28 (9.04)*	15.17 (10.1)*†
Players involved (n)	2.28 (0.83)*†	2.64 (0.85)*†	2.8 (1.26)*†	3.4 (1.47)*†
Ball Touches (n)	7.31 (4.67)	8.47 (5.77)	7.42 (5.45)*	9.64 (6.0)*
Passes (n)	1.61 (1.48)*	2.58 (2.04)*	1.83 (1.68)*	3.03 (2.5)*
Players involved/Duration (n/s)	0.28 (0.18)	0.27 (0.14)	0.29 (0.15)	0.27 (0.11)
Ball Touches/Duration (n/s)	0.72 (0.25)†	0.69 (0.22)	0.64 (0.23)†	0.66 (0.2)
Passes/Duration (n/s)	0.16 (0.13)*	0.2 (0.11)*	0.16 (0.11)*	0.19 (0.11)*
Ball Touches/Players involved (n/n)	3.22 (2.04)†	3.04 (1.48)	2.55 (1.22)†	2.83 (1.31)
Passes/Players involved (n/n)	0.59 (0.48)*	0.87 (0.56)*	0.55 (0.36)*	0.77 (0.5)*
Passes/Ball Touches (n/n)	0.21 (0.16)*	0.29 (0.15)*	0.24 (0.15)*	0.29 (0.15)*
FINALIZATION				
Shots (n)	0.39 (0.56)†	0.5 (0.64)†	0.24 (0.53)†	0.28 (0.52)†
Goals/Shots (n/n)	0.38 (0.48)	0.17 (0.36)	0.29 (0.44)	0.26 (0.44)
OFFENSIVE SEQUENCES	103	102	107	86

* Significant difference ($p<0.05$) between experience levels in each SSG format.

† Significant difference ($p<0.05$) between SSG formats in each experience level.

Table 2*Results of the offensive sequences (absolute frequencies) performed by groups in each SSG format.*

		Results of the Offensive Sequences			Total
		Total Success	Partial Success	Unsuccessful	
N-Exp	3 vs. 3 + GKs	14	7	82	103
	6 vs. 6 + GKs	7	2	98	107
Exp	3 vs. 3 + GKs	9	10	83	102
	6 vs. 6 + GKs	6	6	74	86
Total		36	25	337	

Discussion

Experience effects on the offensive performance in each small-sided game

The purpose of this paper was to analyze the interaction and main effects of deliberate practice experience and SSG format on the offensive performance of young soccer players. Although no significant interaction effects were observed between independent variables, results indicate that the experience level and the SSG format significantly influenced the offensive performance of young athletes.

In this investigation, deliberate practice experience refers to the average value of 3.87 years of soccer training for participants from the Exp group. Despite some differences in the aims and methods, data obtained concur with studies of Ward and Williams (2003), Williams and Hodges (2005), and Ford and Williams (2012) who observed that the experience is an aspect which influences the competitive performance that is directly related to the time of practice and competition in soccer. Nevertheless, it seems that it does not require long periods of deliberate practice in order to verify differences in the collective performance comparatively to youngsters who only play the game for enjoyment and fun (i.e., deliberate play).

In both SSGs, the level of experience in soccer had a significant effect on performance indicators which characterize the development of offensive sequences. The observed effect sizes on

simple and composite performance indicators are higher than the recommended minimum effect size representing a practical significant effect (i.e., $\eta_p^2=0.04$), and ranged from small to moderate (Ferguson, 2009). As an individual constraint, the deliberate practice experience should be considered by researchers or coaches when analyzing game performance or designing talent developmental programs in youth soccer.

Experienced participants performed significantly longer offensive sequences, with a greater number of players involved, who, in turn, executed more touches on the ball and more passing actions. The main difference observed in the composite indicators suggests that the Exp group adopted a "possession play" style, which implies a more intensive and variable ball circulation. The non-experienced participants showed a tendency to build offensive sequences through individual actions, possibly trying to quickly explore the defensive disorganization that is common in lower skill levels. In this group, offensive sequences were, on average, shorter and involved fewer players, which is associated with the execution of a lower number of passes. This style of play is usually observed in novice players, whose tendency is to perform individual actions to solve contextual problems during matches.

Williams (2000) stated that the ability to "read the game" distinguishes skilled from less skilled soccer players. Several studies have shown that expert players are faster and more accurate to recognize and recall patterns of play, demonstrate

more effective and efficient visual search strategies and make better decisions in competitive contexts (Vaeyens et al., 2007). Since the soccer game is an eminently tactical reality, these aspects of perceptual-cognitive nature are plausible enough to perceive the differences verified in both groups. Especially in 6 vs. 6 + GKs, experienced participants differed even more from the N-Exp group by producing longer offensive sequences with a greater number of ball touches. Mastery of specific motor skills such as ball control, pass or dribble allows teams to maintain ball possession during longer periods and, therefore, to exploit the weaknesses of the opponent defensive organization in the most appropriate moments. Nevertheless, the "possession play" style does not relate exclusively to the superior technical ability of the more experienced players, but essentially to the ability to establish an effective unity of cooperation among team players (Reilly, 2005). From this perspective, "reading the game" must be a quality to develop since the early stages of training with young soccer players.

The differences observed between groups for the indicators that characterize the finalization of offensive sequences were not statistically significant either in 3 vs. 3 + GKs or 6 vs. 6 + GKs games. These results support the investigation of Reilly et al. (2000), which evidenced no significant differences in shooting test between U-16 elite and sub-elite players. The overview of the development and finalization of offensive sequences allows us to infer that the N-Exp group scored more goals using faster offensive methods, predominantly built through individual actions. Instead, the Exp group made more shots and scored fewer goals, executing more passes and involving more players in the process. Finally, we emphasize that the number of passes made in the offensive sequences led to major differences ascertained between groups of participants. This finding prompts us to agree with Redwood-Brown (2008), who mentioned that the execution of accurate passes contributes not only to create scoring opportunities, but also to restrict the possession of the opposite team, and, ultimately, to achieve success in soccer.

Effects of small-sided games on the offensive performance at each level of experience

The development of sport expertise

should be regarded as being influenced by an interaction of internal and external constraints (Araújo et al., 2010). As far as we are aware, the deliberate practice experience (individual constraint) and the manipulating of pitch size and number of players (task constraint) have not been previously analyzed simultaneously. In this study, the configuration of the SSG format manifested a significant effect on the offensive sequences' characteristics, except for the composite indicators of the Exp group. Partial eta squared values (effect sizes) ranged from small (composite indicators of N-Exp group) to moderate (simple indicators of both groups) (Ferguson, 2009). Such evidence confirms that manipulating task constraints may induce modifications in specific behaviors of players and, thereby, foster the development and improvement of technical, tactical, and strategic skills in team sports (Williams and Hodges, 2005; Almeida et al., 2012).

In terms of the development of offensive sequences, both SSGs differed significantly in the rhythm of intervention on the ball and the number of consecutive ball touches carried by each player, yielding higher values in 3 vs. 3 + GKs. Data from the N-Exp group confirmed findings from other investigations (Capranica et al., 2001; Jones and Drust, 2007; Duarte et al., 2009; Hill-Haas et al., 2009; Kellis and Katis, 2009; Casamichana and Castellano, 2010), in which each player revealed a more effective relationship with the ball in smaller game formats. The Exp group exhibited greater stability in collective performance profiles between both game formats. The duration of ball possession and the number of players involved in the offensive sequences presented higher values in 6 vs. 6 + GKs, which underscore the ability of the experienced teams to keep the ball in larger pitch sizes and involving more players.

Considering the finalization of offensive sequences, the number of shots was significantly higher in 3 vs. 3 + GKs in both groups, although this did not reflect on the effectiveness of shots. The non-experienced participants were more successful in 3 vs. 3 + GKs games, because they scored more goals, executed more shots on goal and produced less unsuccessful offensive sequences in this game format. In 3 vs. 3 + GKs, the experienced players not only concluded more

successful (total and partial) offensive sequences, but also ended more unsuccessful offensive sequences. Decreasing the pitch size and players' number provided an increase in the number of shots and goals. Such facts are consistent with previous studies (Katis and Kellis, 2009; Casamichana and Castellano, 2010), which revealed that players had more opportunities for shooting and scored more goals in smaller game formats.

Deliberate practice experience and small-sided games: practical implications

Overall, 3 vs. 3 + GKs games ensure that players will get more directly involved in the match, since they contact more often with the ball, execute accurate passes and shoot on goal more frequently. This evidence seems to be especially important for the N-Exp group. The non-experienced participants demonstrated a poorer adaptation to 6 vs. 6 + GKs, explained by differences recorded in the results of offensive sequences and especially by the greater number of unsuccessful offensive sequences in this game format. Our data suggested that the game format clearly affects the quantity and quality of performed actions and, consequently, the offensive sequences' characteristics. Katis and Kellis (2009) argued also that SSGs can serve several purposes as specific means of training. According to Reilly (2005), since young players need to develop physical abilities, technical skills and decision making in specific performance contexts, it makes sense to use SSGs depending on the age of the participants. However, youth soccer coaches should be aware that age is not a very precise variable to use in the organization of the training task. Even within the same age group, it is possible to note considerable differences in individual and collective performance of players

with well distinct skill and experience levels.

In summary, the present paper has evidenced that the deliberate practice experience (individual constraint) and the SSG format (task constraint) do not depend of each other (interaction effect) to influence the offensive performance of young soccer players. Both factors affected independently the characteristics of the offensive sequences. Findings confirm that SSGs can serve several purposes as specific means of training. However, for effective skill acquisition and performance enhancing in youth soccer, the manipulation of pitch size and number of players should always consider the players' individual constraints. In this sense, smaller game formats seems to be particularly suitable for novice athletes (e.g., children/youngsters without experience and/or with a lower skill level), since they constrain the development of sport-specific skills based on a major involvement with the ball. On the other hand, in larger SSG formats, the number of actions that each player performs on the ball tends to decrease, increasing the number of "off-the-ball" movements and the need to form an effective unit of cooperation with teammates. Such game formats may be useful to practice the specific movement requirements of competitive situations (Hill-Haas et al., 2009), and should be carefully considered as young players improve game understanding and specific motor skills.

Further studies should continue to verify how the task constraints imply the efficacy of the learning process in soccer, aggregating different contexts and players' experiences. The functional impact, as far as technical and tactical behavioral changes in consequence of pitch size and number of players' modifications are concerned, should be clarified.

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The Structure of Performance of a Sport Rock Climber

by

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This study is a contribution to the discussion about the structure of performance of sport rock climbers. Because of the complex and multifaceted nature of this sport, multivariate statistics were applied in the study. The subjects included thirty experienced sport climbers. Forty three variables were scrutinised, namely somatic characteristics, specific physical fitness, coordination abilities, aerobic and anaerobic power, technical and tactical skills, mental characteristics, as well as 2 variables describing the climber's performance in the OS (Max OS) and RP style (Max RP). The results show that for training effectiveness of advanced climbers to be thoroughly analysed and examined, tests assessing their physical, technical and mental characteristics are necessary. The three sets of variables used in this study explained the structure of performance similarly, but not identically (in 38, 33 and 25%, respectively). They were also complementary to around 30% of the variance. The overall performance capacity of a sport rock climber (Max OS and Max RP) was also evaluated in the study. The canonical weights of the dominant first canonical root were 0.554 and 0.512 for Max OS and Max RP, respectively. Despite the differences between the two styles of climbing, seven variables – the maximal relative strength of the fingers (canonical weight = 0.490), mental endurance (one of scales : The Formal Characteristics of Behaviour–Temperament Inventory (FCB–TI; Strelau and Zawadzki, 1995)) (-0.410), climbing technique (0.370), isometric endurance of the fingers (0.340), the number of errors in the complex reaction time test (-0.319), the ape index (-0.319) and oxygen uptake during arm work at the anaerobic threshold (0.254) were found to explain 77% of performance capacity common to the two styles.

Key words: sport climbing, canonical analysis, structure of performance.

Introduction

Researchers have been attracted to rock climbing since late 1970s, partly because of its increasing popularity and also due to the rising interest in making it one of the Olympic sport disciplines. Recently, research has concentrated on sport climbing where climbers are protected against falling from a height by permanent protection points installed along climbing routes. At present, these precautions are typical of events involving artificial climbing walls, as well as being frequently used during outdoor climbing

events, mostly on rocks rising several tens of meters high.

The performance of sport rock climbers is judged by their ability to complete a route presenting a certain level (grade) of technical difficulty in one of three climbing styles. The most popular styles are defined based on whether climbers set out to complete a route without any previous knowledge of it (*on sight* – OS), or whether they successfully reach the endpoint without falling off after gaining some experience of the route during earlier trials (*red point* – RP).

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Although the number of studies dealing with this sport has grown, the results are conflicting (Espana-Romero, 2009; Giles et al., 2006; Watts, 2004), probably because of the complex and multifaceted nature of climbing. These circumstances provided grounds for attempting to identify the structure of climber's performance by means of canonical analysis, a tool of multivariate statistics.

Previous studies on sport climbing (Mermier et al., 2000; Giles et al., 2006) used regression analysis to find correlations between one dependent variable Y and a set of independent variables $\{X_1, \dots, X_n\}$. This approach has been found insufficient, though, when the object of analysis is a set of dependent variables $\{Y_1, \dots, Y_n\}$. The canonical analysis is used in such cases and it seeks correlations between two sets (vectors) of variables. Basically, canonical analysis aims:

- to find uncorrelated canonical variables that explain an increasingly large amount of variance in two sets,
- to calculate canonical weights describing each variable's „pure“ contribution to the canonical variable,
- to calculate factor loadings that determine each variable's correlation with the canonical variable,
- to calculate the extracted variance and then redundancy showing the average amount of variance in one data set that the canonical variable explains through the variables of the second set.

Although used as a means of studying other sport disciplines (Babić et al., 2007; Blažević, 2009; Malacko, 2010), canonical analysis has never been applied to explore the structure of performance in sport rock climbing. In this study, it was chosen to answer the following research questions:

- which variables explain the climber's performance in sport rock climbing to the highest degree, regardless of the climbing style?
- how do the sets of various mental, technical and physical characteristics affect two dependent variables: best performance in the OS style and best performance in the RP style?
- how are the vectors of the three sets of characteristics correlated?

Material and Methods

Thirty Polish advanced male climbers (average performance in the OS style: 7b+ (7a - 8a); average performance in the RP style: 8a (7b+ - 8b+/8c) volunteered to participate in this study. This group was analysed previously in research of Magiera and Rygula (2007). Their age was 27 ± 5.45 years, the climbing experience 8.4 ± 3.46 years and the weekly training time 10 ± 3.59 hours. The methods for data collection were direct observation. Physiological, motor and psychological tests were carried out under standard conditions. Most of the tests were dedicated to sport climbing, climber's experience and age.

The variables included 45 somatic and mental characteristics, specific physical fitness, coordination abilities, aerobic and anaerobic power, technical and tactical skills. Self-reported onsight (Max OS) and redpoint (Max RP) climbing performance were determined as the most difficult. To ensure that the route grading systems were comparable and to make them useful for mathematical analyses, a decimal scale (Köstermeyer, 2000) and a conversion table were used. The description of measuring instruments has been omitted. Their detailed description can be found in the study of Magiera (2006).

The first step in the subsequent statistical analysis was the calculation of basic statistical measures, such as an arithmetic average ($\bar{X}$), standard deviation (S), coefficient of variation (V), coefficient of asymmetry (A_s), and coefficient of kurtosis (K_u-3) (Table 1). Further mathematical and statistical analysis utilised a multivariate exploration technique – canonical analysis. The statistically significant correlations between two different sets of variables were sought using: λ – significance of the square of canonical correlation, R_c – the canonical correlation value, R_c^2 – the values of the squares of canonical correlations, χ^2 – chi-square values of Bartlett's test, and p – statistical significance at < 0.05 (Malacko, 2010).

Results

To be able to answer the question „Which characteristics explain the climber's performance in sport rock climbing to the highest degree, regardless of the climbing style?“ two sets of variables were compared:

- dependent variables – *Max OS* and *Max RP*
- independent variables – common characteristics obtained from two regression equations *Max OS* and *Max RP*.

The findings from the analysis of the two sets of variables are shown in Table 2.

The next step of the research involved the calculation of the values of the variables and their canonical correlations and testing them for significance. Two canonical variables were calculated, whose correlations (R_c) for the first and second variable were 0.94 and 0.54, respectively. Both correlations were statistically significant ($p < 0.05$), thus showing that the model described both data sets well. With the calculation of the variance and redundancy values it was possible to identify the amounts of variance explained by particular canonical variables. The first root extracted from the performance indicators (*Max OS* and *Max RP*) around 88% of the variance, while the second one only 12%. The redundancy value for the first root indicated that the independent variables (set II) explained 77% of the variance in climbing performance ($p < 0.05$). Because the first canonical variable explained a much larger amount of the variance (81%) than the total redundancy value, it was concluded that it described the analysed phenomenon well. Hence further analysis concentrated on this variable.

By looking at the factor structure of the above sets of variables the correlations between the canonical roots and the variables in the set could be identified. The factor loadings of the first root were very similar (*Max OS*: -0.94; *Max RP*: -0.93), showing that both the results were equivalent and that neither of the climbing styles tended to dominate. The factor loadings of the first root for the independent variables were the following: Ape index: 0.303, CTR-errors: 0.445, Finger strength: -0.554, E70%z10/10: -0.035, $VO_{2AT_{Arm}}$: -0.558, TEMP-ME: 0.256, Technique: -0.622.

Therefore, the first canonical variable was represented by two equations:

$$U_1 = 0.554 \times \text{Max OS} + 0.512 \times \text{Max RP}$$

$$V_1 = -0.319 \times \text{Ape index} - 0.319 \times \text{CTR-errors} + 0.490 \times \text{Finger strength} + 0.340 \times \text{E70\%z10/10} + 0.254 \times \text{VO}_{2AT_{Arm}} - 0.410 \times \text{TEMP-ME} + 0.370 \times \text{Technique}$$

The canonical analysis was also useful in

determining how a set of different characteristics (technical, physical and mental) affected two dependent variables *Max OS* and *Max RP* used in the study, thus giving the answer to the second research question.

To make comparisons more efficient, eight characteristics were selected from each of the three sets of climbers' mental, technical and physical attributes (Table 3). The first and most significant canonical correlations in the new sets of mental characteristics (personality traits, temperament, locus of control and tactics), technical characteristics (coordination and technique) and physical characteristics (somatic, flexibility, physical fitness and efficiency) were high, the canonical R being 0.82, 0.81 and 0.79, respectively. All correlations were statistically significant ($p < 0.001$). The total redundancy values for the three sets interpreted as average percentages of the variance in one set of variables that all canonical variables explained based on another set were differentiated. This means that in analysing climber's performance (the *Max OS* and *Max RP* set) eight mental characteristics explained 41% of the variance, eight technical characteristics – 53%, and eight physical characteristics – 62%.

The canonical analysis helped answer the third question too. The first to be analysed were the sets of somatic and physical fitness characteristics and that of coordination and technique (Table 4, columns 2 and 3). The total canonical R was high (0.82) and statistically significant ($p < 0.001$). The canonical roots in the right set (the vectors of physical characteristics) explained almost 32% of the variance in the left set of variables (technical characteristics). Reversely, the first set explained 29% of the variance. The results obtained from comparing the characteristics of personality, temperament, locus of control and tactics with the somatic and physical fitness characteristics (Table 4, columns 4 and 5) showed that the right set (mental characteristics) explained almost 30% of the variance in the left set (physical characteristics). In the reverse situation, the rate of the explained variance declined to 25%. The total canonical R was both high (0.83) and statistically very significant ($p < 0.001$). The sets of mental and technical characteristics were compared last (Tables 4, columns 6 and 7). The total canonical R was similar to its values determined from the

previous analyses (0.82) and also statistically very significant ($p < 0.001$). The canonical roots of both

the right set and the left set explained a similar amount of the variance – 38%.

Descriptive statistics

Table 1

N	Variables		X	S	V	A _s	K _{r-3}	
1.	Max OS	Best performance in OS style	n	8,68	0,53	6,08	-0,05	-1,39
2.	Max RP	Best performance in RP style	n	9,55	0,55	5,80	0,22	-1,12
3.	Mass	Body mass	kg	68,85	5,02	7,30	-0,73	1,22
4.	Height	Height	cm	177,90	5,59	3,14	0,04	-0,94
5.	Arm span	Arm span	cm	180,09	7,02	3,90	-0,10	-1,15
6.	Ape index	Ape index: arm span/height	cm/cm	1,01	0,02	2,33	0,63	0,38
7.	FM%	% of fat tissue	%	10,42	3,28	31,47	0,27	-0,50
8.	MM%	% of muscle tissue	%	63,77	8,30	13,01	0,31	0,40
9.	BMI	Body Mass Index	kg/m ²	21,82	1,70	7,78	-0,03	-0,30
10.	BCMI	Body Cell Mass Index	kg/m ²	11,35	2,03	17,86	0,19	-0,24
11.	Hip flexion	Range of motion of hip flexion	st.	118,67	9,95	8,38	0,09	-1,42
12.	Hip abduct	Range of motion of hip abduction	st.	51,30	6,95	13,55	-0,19	0,29
13.	Froggies	Flexibility of hips in “froggies”	cm	6,11	5,10	83,41	0,23	-0,24
14.	CRT- errors	Complex reaction time – number of errors	n	5,87	2,79	47,54	-0,11	-0,78
15.	Stereometry	Stereometry	mm	14,33	10,09	70,36	1,05	0,08
16.	Balance-inst	State of balance – instability	st./s	260,98	54,45	20,86	-1,64	2,95
17.	Balance-ic	State of balance – locus of control	n	81,80	8,80	10,76	0,13	-0,84
18.	Adapt-error	Motor adaptation – error	S*T	168,13	55,77	33,17	0,83	-0,14
19.	Adapt-rate	Motor adaptation – adaptation rate	s	0,84	0,25	30,09	1,53	2,74
20.	Different	Differentiation	%	87,50	11,53	13,18	-1,08	0,93
21.	Finger strength	Maximal finger strength	kg/kg	0,55	0,06	11,39	-0,33	-0,37
22.	E70%z10/10	Finger endurance 10/10s 70%Fmax	s	358,80	198,67	55,37	1,57	2,02
23.	Arm strength	Arm strength	kg/kg	1,64	0,12	7,44	0,16	-0,63
24.	Arm endurance	Arm endurance	s	67,43	13,68	20,28	0,03	-0,97
25.	W30s-Wtotal	Total work of the upper body - W30s	J/kg	157,37	11,50	7,31	-0,93	1,16
26.	W30s-Pmax	Maximal power of the upper body - W30s	W/kg	6,43	0,38	5,92	-0,46	0,41
27.	W30s-Fatigue	Fatigue index - W30s	%	17,90	3,10	17,29	-0,11	-0,56
28.	W30s-T attain	Time of maximum power attainment - W30s	s	7,46	0,91	12,24	0,94	0,83
29.	W30s-T maint	Time of maximum power maintenance - W30s	s	4,48	0,92	20,47	-0,15	-0,50
30.	VO ₂ max _{Arm}	Maximal oxygen uptake –arm work	ml/kg/min	36,32	6,64	18,29	-0,32	-0,16
31.	VO ₂ AT _{Arm}	Oxygen uptake at anaerobic threshold – arm work	ml/kg/min	24,37	5,52	22,66	-0,26	-0,69
32.	SI	Spatial intelligence	n	36,17	9,48	26,22	-1,18	0,50
33.	LC	Locus of control	n	10,53	4,32	40,97	0,35	0,16
34.	OSB-N	Neuroticism – raw values	n	6,13	3,90	63,64	0,45	-0,43
35.	OSB-E	Extroversion – raw values	n	14,60	5,03	34,47	-0,46	-0,44
36.	OSB-P	Psychotism – raw values	n	10,70	4,18	39,09	-0,28	-0,15
37.	OSB-L	Lying – raw values	n	8,87	3,31	37,35	0,65	0,40
38.	TEMP-BR	Briskness – raw values	n	16,43	2,76	16,82	-0,50	-0,44
39.	TEMP-PE	Perseverance – raw values	n	10,33	4,40	42,56	-0,09	-0,46
40.	TEMP-SS	Sensory sensitivity – raw values	n	13,27	4,39	33,07	-0,61	-0,06
41.	TEMP-ER	Emotional reactivity – raw values	n	6,93	4,37	63,06	0,20	-1,01
42.	TEMP-ME	Mental endurance – raw values	n	12,57	4,99	39,68	-0,83	-0,39
43.	TEMP-AC	Activity – raw values	n	11,83	3,85	32,49	-0,21	-0,95
44.	Tactics	Climbing tactics	%	88,37	7,47	8,45	-0,31	-0,54
45.	Technique	Climbing technique	n	51,07	3,01	5,90	0,22	-0,12

Table 2*The results of canonical analysis and the chi-square test (30n)*

	Left	Right
Number of variables	2	7
Extracted variance	100.00%	32.03%
Total redundancy	80,57%	20.76%
Variables: 1	Max OS	Ape index
2	Max RP	CRT - errors
3		Finger strength
4		E70%z10/10
5		VO ₂ AT _{Arm}
6		TEMP-ME
7		Technique

	Rc	Rc ²	χ ²	df	p	λ
0	0.935	0.875	131.186	14	0.000	0.088
1	0.542	0.294	18.863	6	0.004	0.705

*Canonical R: 0.93546 χ^2 (14)=131.19 p=0.0000***Table 3***The results of canonical analysis for selected mental, technical and physical characteristics with respect to the dependent variables Max OS and Max RP*

	Mental characteristics		Technical characteristics		Physical characteristics	
	Canonical R: 0.815		Canonical R: 0.812		Canonical R: 0.815	
	Chi2(16)=73.130		Chi2(16)=82.033 p=0.000		Chi2(16)=73.130 p=0.000	
	p=0.000					
	Left	Right	Left	Right	Left	Right
Variance	100.00%	27.84%	100.00%	26.15%	100.00%	37.55%
C. redund.	40.77%	10.85%	52.89%	11.98%	61.81%	20.37%
1	Max OS	LC	Max OS	CRT-errors	Max OS	Mass
2	Max RP	OSB-N	Max RP	Stereometry	Max RP	Ape index
3		OSB-P		Balance-inst		FM%
4		TEMP-BR		Balance-lc		Hip flexion
5		TEMP-PE		Adapt-error		Finger strength
6		TEMP-SS		Adapt-rate		E70%z10/10
7		TEMP-ME		Different		Arm strength
8		Tactics		Technique		VO ₂ AT _{Arm}

Table 4

The results of canonical analysis showing correlations between the vectors of the sets of mental, technical and physical characteristics.

	Technical and physical characteristics		Mental and physical characteristics		Mental and technical characteristics	
	Canonical R: 0.815 Chi2(64)=170.42 p=0.000		Canonical R: 0.829 Chi2(64)=146.44 p=0.000		Canonical R: 0.815 Chi2(64)=193.27 p=0.000	
	Left	Right	Left	Right	Left	Right
Variance	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
C. redund.	31.80%	29.18%	30.33%	25.28%	37.80%	38.18%
1	CRT-errors	Mass	LC	Mass	LC	CRT-errors
2	Stereometry	Ape index	OSB-N	Ape index	OSB-N	Stereometry
3	Balance-inst	FM%	OSB-P	FM%	OSB-P	Balance-inst
4	Balance-lc	Hip flexion	TEMP-BR	Hip flexion	TEMP-BR	Balance-lc
5	Adapt-error	Finger strength	TEMP-PE	Finger strength	TEMP-PE	Adapt-error
6	Adapt-rate	E70%z10/10	TEMP-SS	E70%z10/10	TEMP-SS	Adapt-rate
7	Different	Arm strength	TEMP-ME	Arm strength	TEMP-ME	Different
8	Technique	VO ₂ AT _{Arm}	Tactics	VO ₂ AT _{Arm}	Tactics	Technique

Discussion

The available studies determine climber's performance from questionnaire surveys (where the respondents are asked to state the most difficult route they have completed in the OS or RP style) (Booth et al., 1999; Espana-Romero et al., 2009; Ferguson and Brown, 1997; Grant et al., 2003; Müller and Held, 1992; Sheel et al., 2003), based on the score in a climbing test carried out in a setting made to resemble a lead climbing event (Mermier et al., 2000), or by calculating an Athlete Development Indicator (ADI) by means of the Hellwig's algorithm (Magiera and Ryguła, 2007). Whatever the approach, the test batteries invariably address one, special type of performance achievable in different climbing styles or in different climbing settings (indoor or outdoor).

The approach taken in this study allowed to look at climbing performance from a somewhat broader perspective. Canonical analysis provided *Max OS* and *Max RP* performances which were taken to represent the overall performance capacity of a sport rock climber. The analysis found the following variables to be significant in the equation of the dominant first root: maximal

relative strength of the fingers (*Finger strength*: 0.490), mental endurance (*TEMP-ME*: -0.410) and technique (*Technique*: 0.370), followed by isometric endurance of the fingers (*E70%z10/10*: 0.340), the number of errors in the complex reaction time test (*CRT-errors*: -0.319), ape index (-0.319) and oxygen uptake during arm work at the anaerobic threshold (*VO₂AT_{Arm}*: 0.254). These seven characteristics described the climber's overall performance capacity well, explaining 77% of its variance. This may mean that despite their distinctive requirements, climbing styles are of little effect on performance unlike climber's general abilities. Other available studies only deal with some of the model variables.

Notwithstanding the aforementioned disagreement over what determines sport climber's performance, many studies treat finger strength as a prerequisite for its high level (Espana-Romero et al., 2009; Giles et al., 2006; MacLeod et al., 2006; Quaine and Vigouroux, 2004; Watts, 2004). This study confirmed this view. According to the canonical values, this variable (*Finger strength*) was the most significant. The greater maximal strength of the four fingers (without the thumb), particularly in relation to

climber's body mass, the better performance in climbing.

Earlier studies tended to give more attention to climber's endurance. This ability has been assessed with many different tools, but recently tests evaluating the isometric endurance of the finger flexors have come to the fore (Ferguson and Brown, 1997; MacLeod et al., 2006; Quaine et al., 2003), as well as tests utilising climbing ergometers (España-Romero et al., 2009; Köstermeyer, 2000). The results of the first type of tests have showed that better forearm vascular capacity increases climber's performance during the workload-relaxation sequence by allowing more blood to be supplied to muscles between contractions. In the second case, the climbing time (España-Romero et al., 2009) or the distance completed in a test with a climbing ergometer (Köstermeyer, 2000) have been strongly correlated with performance, particularly in experienced climbers. Maximal oxygen uptake in the incremental test to exhaustion did not differentiate the subjects (España-Romero et al., 2009), but the distance completed in a state of functional equilibrium has been found to significantly affect the endurance test results (Köstermeyer, 2000). These findings are confirmed by variables $E70\%z10/10$ and $VO_{2AT_{Arm}}$ used in this study.

The role that the 'ape index' variable (the arm span to height ratio) plays in the model has not been fully explained. Inversely proportional effect of this variable on performance may be controversial. The authors assume that the arm span which does not differentiate most climbers in most cases (España-Romero et al., 2009) is less important than having a slimmer body (i.e. a smaller shoulder width). This opinion requires further investigations.

Canonical analysis was used in this study also to identify the structure of performance of sport rock climbers with respect to their various technical, physical and mental characteristics. Previous studies sought relationships between performance and particular somatic, physical fitness, physiological or mental characteristics. Interdisciplinary papers analysing climbers from many angles are not available. An exception is the studies carried out by Mermier et al. (2000) and Magiera and Ryguła (2007).

In the Mermier et al.'s study (2000) the

principal component analysis (PCA) allowed extracting three components which were called „a training component" (the strength of the arms and legs and of the full-hand grip, the anaerobic power of the upper and lower body, arm endurance, % fat, climbing performance), „an anthropometric component" (body mass and height, the length of the lower extremities, arm span, ape index), and „a flexibility component" (the hip-joint range of motion). The authors have proven that being successful in climbing depends on the interaction of many factors rather than on a single factor, as suggested before. Multiple regression of the relationships between the three components and the subjects' overall scores in two climbing trials showed that the components explained 58.9% (training), 0.3% (anthropometric) and 1.8% (flexibility) of the total variance in performance. The authors themselves suggested that more in-depth studies allowing also for mental and technical characteristics and technical and tactical skills were necessary to explain the remaining 34% of the variance in climbing performance.

The primary research purpose of the Magiera and Ryguła study (2007) was to build a biometric model describing the best performance of male climbers in the OS style based on an Athlete Development Indicator (ADI). It was almost completely ($R^2=0.93$) explained by 9 variables providing the best description of this phenomenon: technical skills, oxygen uptake during arm work at the anaerobic threshold, maximal relative strength of the fingers, locus of control, psychotism, strength endurance, ape index, the number of errors in the complex reaction time test and the range of motion during hip flexion.

Scientists studying this sport discipline have also made attempts to assess how particular attributes of climbers contribute to their performance. Hörst (2003), who is an author of many popular climbing handbooks, views rock climbing as a unique sport where the athlete is required to demonstrate almost a complete balance of mental characteristics, technical skills and physical abilities. He contrasts it with sports where performance is mainly determined by physical characteristics (100m sprint) or technical skills (golf) (Figure 1). Unfortunately, it is only a subjective opinion of the author, without any

scientific background.

Guidi has a different opinion in regard to this topic. In his report published on the official website of the FFME (Fédération Française de la Montagne et de l'Escalade) Guidi presented the findings of an expert commission consisting of the FFME coaches (Guidi, 2002). Among other things, he analysed the structure of climbers'

performance in the lead and bouldering events (Figure 2). According to Guidi, the key factors determining performance in the first event were mental characteristics (50%), then physical (27%), tactical (15%) and technical (8%) ones.

Figure 1

The relative requirements of different sports (Hörst, 2003)

Figure 2

The structure of sport climber's performance in the lead and bouldering events (Guidi, 2002)

Figure 3

Percentage contributions and the complementarity of different sets of characteristics explaining climber's overall performance capacity (Max OS and Max RP)

The findings of this study where the issue of climber's performance has been given comprehensive treatment allowed empirical verification of the above opinions. According to the results of the canonical analysis (Table 3) and their totals (Figure 3), three sets of characteristics, each having 8 selected variables, explained climbers' overall performance capacity in 96% (Max OS and Max RP). The chart below tends to support the Hörst's opinion (2003) that rock climbing requires harmoniously developed physical fitness, technical and tactical skills, as well as mental preparation. The percentage contributions of particular sets of variables to explaining performance were similar, but not equal. The characteristics of physical fitness (*Finger strength*, $E70\%z10/10$, *Arm strenght*), body efficiency (VO_2AT_{Arm}) and anthropometric (*Body mass*, *Ape index*, $FM\%$, *Hip flexion*) explained the most – 38%, while mental characteristics were found to be the least significant in this respect (25%). The present-day sport climbing is safer for contestants (owing to permanent protection points, strong ropes, etc.). Climbers are viewed

today as gymnasts exercising on the rock rather than people risking their lives en route to the top. This safety and the outstanding experience of the examined climbers not only seem to explain the relatively low share of mental attributes in the structure of their performance, but also highlight the prominence of the physical aspects of their training.

This study has shown that sport climbing performance is determined by different sets of morphofunctional characteristics. Keeping the sets apart has only a theoretical advantage, because they are in fact complementary and overlap (Figure 3). Climbers, particularly the less trained ones, frequently utilise this interaction to compensate for their deficiencies with better developed skills and abilities. The canonical analysis may be a measure to find out whether variables in one set may serve as predictors of the values of the variables in another. All three sets of characteristics (physical, mental and technical) used in this study explained the variance similarly (in around 30%), but the strongest relationship was found between the set containing selected

characteristics of personality, temperament, locus of control and tactics, and the set with coordination abilities and technique (38 %). This seems to explain why the two groups of characteristics have a similar informative value. The climbers' physical characteristics were explained least effectively by their mental attributes (25%), which reveals a relatively weaker relationship between the results of selected mental tests and the somatic, physical fitness, aerobic and anaerobic power of the climbers

This study focused on advanced male climbers taking part in rock climbing events. For different sex and experience of the subjects, type and setting of the events (indoor or outdoor), the results may be different.

Conclusions

A thorough study of training efficiency of advanced sport climbers involves testing of their physical, technical and mental characteristics. The three sets of characteristics used in this study explained the structure of climbing performance to a similar, but unequal degree, i.e. in 38, 33 and 25%, respectively. The sets were also found to be complementary to around 30% of the variance. The study determined also the overall performance capacity of outdoor climbers. Although the OS and RP climbing styles pose different requirements, seven variables explained 77% of climber's overall performance capacity common to the two styles. An insight into its structure was enabled by the canonical analysis, a tool of multivariate statistics.

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The Effects of a Maximal Power Training Cycle on the Strength, Maximum Power, Vertical Jump Height and Acceleration of High-Level 400-Meter Hurdlers

by

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The aim of this study was to determine the effects of a power training cycle on maximum strength, maximum power, vertical jump height and acceleration in seven high-level 400-meter hurdlers subjected to a specific training program twice a week for 10 weeks. Each training session consisted of five sets of eight jump-squats with the load at which each athlete produced his maximum power. The repetition maximum in the half squat position (RM), maximum power in the jump-squat (W), a squat jump (SJ), countermovement jump (CSJ), and a 30-meter sprint from a standing position were measured before and after the training program using an accelerometer, an infra-red platform and photo-cells. The results indicated the following statistically significant improvements: a 7.9% increase in RM ($Z=-2.03$, $p=0.021$, $\delta=0.39$), a 2.3% improvement in SJ ($Z=-1.69$, $p=0.045$, $\delta=0.29$), a 1.43% decrease in the 30-meter sprint ($Z=-1.70$, $p=0.044$, $\delta=0.12$), and, where maximum power was produced, a change in the RM percentage from 56 to 62% ($Z=-1.75$, $p=0.039$, $\delta=0.54$). As such, it can be concluded that strength training with a maximum power load is an effective means of increasing strength and acceleration in high-level hurdlers.

Key words: resistance training, high-level hurdlers, muscular strength, athletics, testing.

Introduction

Strength training has become an essential method for optimizing athletic performance, especially in sports where explosive strength and speed are key determinants (Baker and Newton, 2008; Cronin and Sleivert, 2005; Lopez-Segovia et al., 2010; Marques, 2010). In light of this, numerous authors have studied the strength changes produced in different athletic activities (e.g. jumps, sprints, or maximum repetitions) as a result of power-centered training (Cormie et al., 2010; Hunter and Marshall, 2002; May et al., 2010; McBride et al., 2002; Mujika et al., 2009; Pui-Lam et al., 2010; Rahimi and Behpur, 2005; Tricoli et al., 2005; Turbanski and Schmidtbleicher, 2010). Research on short distance running is still, however, scarce.

Satkunskiene et al. (2009) studied the changes produced in seven high-level sprinters after eight weeks of power training and found that their stride length and frequency, speed over a 40-meter sprint, and other biomechanical variables related to running technique improved significantly in these athletes. However, the training intensity of these athletes was unclear and not well individualized. Similarly, in another study with young elite sprinters, Blazeovich and Jenkins (2002) highlighted the benefits of power training in terms of variables such as 20-meter sprints or maximal strength in the squat. Thus, after a seven-week training program based on lower-limb exercises (i.e. squats, knee extensions and flexions, and hip extensions and flexions) at 30–50% of one repetition maximum (1RM), the

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performance of these athletes improved significantly in terms of the 20-meter sprint, squat, strength, and isokinetic hip extension and flexion torque at high velocity (i.e., 4.74 rad.s⁻¹).

Despite the fact that the maximum power generated by athletes occurs in highly variable 1RM percentage intervals, which may range from 30 to 80% of the 1RM depending on the training level, the training loads used in most of these studies consider the RM percentage to be a measure of *intensity* rather than an indication of the *power* produced in the training exercises (Dayne et al., 2011; Manning et al., 1986; Stone et al., 2003). As a result, measurement of the 1RM percentage at which maximum power is generated becomes essential when it comes to optimizing the intensity of power training in order to ensure that maximum power stimuli provide greater benefits in explosive sporting activities (Harris et al., 2000).

The training effects of individualized maximum power loads on short sprint performance have seldom been studied. Furthermore, although the athletic specificity of hurdling has been widely studied (Adamczyk, 2009; Iskra and Walaszczyk, 2003; Trzaskoma et al., 2010; Zang and Song, 2001; Zouhal et al., 2010), to the best of our knowledge there has been no research into the effects of power training in hurdlers. In addition, although muscle power may not be the main factor in 400-meter hurdles, it is well known that improved strength has a highly beneficial effect on performance in this type of race (Alejo, 1993; Iskra, 1991; 2012). In light of the above, the purpose of the present study was to determine the effects of maximal power training on maximum strength, maximum power, vertical jump height and acceleration in 400-meter hurdlers. The specific hypothesis was that individualized maximum strength training twice a week for a ten-week period would significantly improve all these variables in elite hurdlers.

Material and Methods

Participants

The sample consisted of seven male, high-level hurdlers (age: 21.7 ± 2.4 years; body mass: 75.1 ± 4.1 kg; body height: 181.8 ± 3.9 cm; personal record: 54.78 ± 2.54 s). All subjects were highly competitive athletes with national and

international success and were selected at a Performance Centre in Spain. Non-random, incidental sampling by viable access was used. The study was carried out in accordance with the Declaration of Helsinki and all subjects collaborated voluntarily. All study procedures were approved by the corresponding research ethics committee.

Design

Due to the small number of high performance athletes available and their varying competitive schedules, it was not possible to include a control group in the experimental design. As such, the study's design was pre-experimental, with a single group and repeated measures (before and after the training cycle). The treatment was applied twice a week for ten weeks, between February and April 2011, during the European under-23 athletics championship season. The dependent variables were 1 repetition maximum (1RM) in the half squat (kg), maximum power in the jump squat (W), flight time in the squat jump (ms), flight time in the countermovement jump (ms), and 30-m sprint from a standing position (s).

Instruments

An Olympic bar with different plates was used to measure the maximum power of the athletes using a MyoTest Pro accelerometer (Myotest SA, Sion, Switzerland) (Crewther et al., 2011). This type of instrument is commonly used to estimate power output by taking into account both the individual's body mass and the external load, as recommended in the scientific literature (Dugan et al., 2004). An infrared Optojump platform (Microgate Corporation, Bolzano, Italy) was used to measure explosive strength (Glatthorn et al., 2011). Speed measurements were performed using a RaceTime 2 Light kit (Microgate Corporation, Bolzano, Italy).

Training cycle

All subjects trained twice a week (Mondays and Wednesdays) for a full cycle of ten weeks, concentrating on their lower limbs. This training consisted of five sets of eight jump squats, with a recovery period of three minutes between sets. These exercises were performed with no countermovements and with the maximum individual load at which each athlete produced maximum power. Athletes were asked

to perform the jump squats as fast as possible and performed their usual training routines, none of which consisted of strength exercises, on the remaining days. All training sessions were supervised by experienced coaches.

Measurement of the variables: sequence and protocol

A pre- and a post-test were carried out before and after the training cycle. These measurements were performed at the same time of day and within one week after a national competition so as to ensure that the athletes were in equivalent competitive shape. Coincidentally, the weather conditions and the athletes' state of hydration and rest were similar on evaluation days. Moreover, all measurements were undertaken according to the protocol proposed by the *National Strength and Conditioning Association* (NSCA) (Earle and Baechle, 2008).

The physical tests began following a general warm-up of about 20 minutes that included light aerobic exercises, stretching and basic low-demand plyometric exercises. After weighing and measuring the athletes, the flight time of the squat jump (ms) and the flight time of the countermovement jump were measured. Each type of the jump was performed twice, with the best of the two results being recorded. Subsequently, and also according to the NSCA protocol, the 1RM of a half squat (kg) was also measured. Once the 1RM had been achieved, and after 10 minutes of recovery, the maximum power produced in the jump squat exercise (W) was measured. This exercise started at 40% of the 1RM for that day and was increased by 5% in each series until reaching maximum power. According to the protocol for the Myotest Pro (Myotest SA, Sion, Switzerland) accelerometer used, each squat jump series consisted of two repetitions, with no countermovement, starting from an initial position in which the thighs were parallel to the ground. Again, only the best jump was recorded. Finally, the athletes ran two 30-meter sprints from a standing start. These sprints were performed on a synthetic track (mondo class) and were performed in spikes. The better of the two results was recorded.

Statistical analysis

The Wilcoxon test ($p < 0.05$) was used to compare the scores obtained by the athletes in the

pre- and post-tests (Newell, 2009). The size effect was also estimated. In light of its suitability as a nonparametric measure of magnitude, Cliff's delta parameter (δ_c) was calculated (Cliff, 1993). In addition, both the percentage change and the values of statistical power were determined. Finally, graphic descriptive statistics were applied after transforming the direct scores into T scores. All these statistical analyses were performed using the SPSS statistics 20 program.

Results

The results (Table 1 and Figure 1) show a statistically significant 7.9% increase in 1RM (kg) ($Z=-2.03$, $p=0.021$, Power=0.70, $\delta_c=0.39$), a 2.3% increase in flight time for the squat jump ($Z=-1.69$, $p=0.045$, Power=0.31, $\delta_c=0.29$) and a 1.43% decrease in the time required for the 30-meter sprint ($Z=1.70$, $p=0.044$, Power=0.46, $\delta_c=0.12$). Moreover, despite not being statistically significant, a 4% increase in maximum power (W) was also observed ($Z=-0.98$, $p=0.16$, Power=0.05, $\delta_c=0.28$). In contrast, no change was observed in flight time for the countermovement jump, with values of close to -0.2% ($Z=-0.77$, $p=0.22$, Power=0.05, $\delta_c=0.00$). Finally, although not contemplated in the initial design for this study, a statistically significant 11% relative percentage change was found for the percentage of 1RM at which maximum power was generated ($Z=-1.75$, $p=0.039$, Power=0.48, $\delta_c=0.54$).

Discussion

Our findings confirm that, after a period of maximum power training, athletes can significantly improve their maximum strength, squat and vertical jumping (greater flight time), and a 30-meter sprint performance while also improving their maximum power, although not in a statistically significant manner. Although the variables determined in the present study are not identical to those measured in previous related studies focusing on different sports disciplines (Harris et al., 2000; Lopez-Segovia et al., 2010; Manning et al., 1986; Marques, 2010; Mujika et al., 2009; Pearson et al., 2009), our results are consistent with those reported previously.

The percentages at which the athletes reached their maximum power are also worth highlighting given that this is a very important variable when it comes to establishing maximum

power training loads (Bevan et al., 2010; Cronin and Sleivert, 2005; Dugan et al., 2004). Thus, the 1RM percentages in this study increased from 56 (measured before training) to 62% (measured after training), which is a statistically significant change. These values, which considerably exceed those reported for the same exercise by other authors (Bevan et al., 2010; Dayne et al., 2011; Naclerio et al., 2008; Stone et al., 2003; Thomas et al., 2007), could be due to the high training level of the subjects. Furthermore, they show that athletes can increase their maximum power and also that they are able to generate more power with each absolute and relative load, thus modifying the force-velocity relationship. This suggests an important effect on the neural mechanisms of force as the speed effort exerted in relation to high loads requires a large number of cellular motor units to be recruited, thus having a positive impact on the rate of force development

(RFD) (Holtermann et al., 2007). However, since no neural adaptations have been investigated in the present study, this remains a hypothesis that could be explored in the future.

This study points to the suitability of power-based training loads (force plus speed) instead of those based simply on the displacement of maximum weight (González-Badillo and Sánchez-Medina, 2010), since, as some authors have pointed out (Kyrolainen et al., 2005), performing each repetition at maximum speed produces significant neuromuscular adaptations which will be reflected in muscular performance. As such, a relevant new research line would involve analyzing the effects of a strength training program whereby each repetition is controlled and adjusted according to predetermined optimum speed values.

Table 1

Pre- and post-test statistical measurements

Variables	Pre M±SD	Post M±SD	Mean difference pre-post	% change	Z Wilcoxon	p	Power	Size (δ_c)
Maximum strength half squat 1 RM (kg)	172.5 ±23.9	186.2 ±26.5	13.7	7.9%	-2.03	0.021*	0.70	0.39
Maximum power JS (W)	3175 ±437	3302 ±507	127	4%	-0.98	0.16	0.18	0.28
SJ flight time (ms)	580.2 ±48.0	594.1 ±54.0	13.9	2.3%	-1.69	0.045*	0.31	0.29
CMJ flight time (ms)	602.6 ±43.9	601.3 ±53.2	-1.3	-0.2%	-0.77	0.22	0.051	0.00
30-m sprint (s)	4.19 ±0.19	4.13 ±0.16	-0.06	-1.43%	-1.70	0.044*	0.46	0.12
% of 1RM for max power	56.25 ±4.43	62.50 ±6.54	6.25	11%	-1.75	0.039*	0.48	0.54

* Statistically significant difference, $p < 0.050$ (unilateral contrast)

Figure 1

Pre/post comparison (variables transformed into T scores).*
Data were transformed into T scores to homogenize the unit of measure.
RM (repetition maximum), Wmax (maximum power),
SJ (squat jump) CMJ, (counter movement jump),
30 m (30 meters sprint), %RM (percentage of the RM).

Here, it is reasonable to expect that strength training would be substantially optimized since it would allow suitable maximum power loads to be specified and each repetition would be controlled to ensure it is performed at the appropriate speed. Furthermore, to achieve a greater understanding of maximum power in 400-meter hurdling, it would be interesting to determine the relationship between the power tests of this study and other tests that are metabolically more similar to those of 400-meter hurdling (e.g., 300-meter) and to analyze the changes that occur while performing the specific power training runs described in the present study.

Finally, an unexpected result of this study, namely that the countermovement jump (CMJ) of the athletes remained unchanged, should be noted. This could be due to the way in which jump squats were performed, with no advantage being taken of the stretch-shortening cycle present in the CMJ. In any case, the previous high CMJ levels for these athletes and the important

improvements produced after training SJ and sprints point to the possibility that they were able to reduce their strength deficit taking advantage of their explosive force. In other words, although the CMJ remained unchanged, the SJ increased, thus showing a higher production of force per time unit with hardly any elastic contribution from the muscle. Further research will be required to confirm the concentric stimuli power effect in the stretch-shortening cycle. The high level of the subjects could also explain this result.

To summarize, despite the methodological limitations of this research (i.e., the lack of a control group and the small sample size), this study provides enough evidence to conclude that the type of power training used increases the performance of high-level hurdlers in terms of maximum strength, maximum power, vertical jump height and acceleration capability. Furthermore, as training should be individualized to achieve maximum results, this requires the specific load that produces maximum power in each athlete to be determined.

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Influence of Inter-Set Stretching on Strength, Flexibility and Hormonal Adaptations

by

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Adequate levels of strength and flexibility are important for the promotion and maintenance of health and functional autonomy as well as safe and effective sports participation. The aim of the present study was to analyze the effects of 8 weeks of strength training with or without inter-set static stretching on strength, flexibility and hormonal adaptations of trained men. Sixteen trained men were randomly divided into 2 groups: the static stretching group (SSG) and passive interval group (PIG). All participants performed 24 training sessions 3 times a week. The test and retest of 8RM, strength, flexibility, cortisol and growth hormone concentration in pre and post test conditions were also evaluated. To compare the differences between and within groups in pre- and post-training tests, ANOVA with repeated measures was performed ($SSG_{pre} \times SSG_{post}$; $PIG_{pre} \times PIG_{post}$; $SSG_{post} \times PIG_{post}$). An alpha level of $p < 0.05$ was considered statistically significant for all comparisons. Both groups showed significant increases in strength (SSG_{pre} vs. SSG_{post} ; PIG_{pre} vs. PIG_{post}) in the same exercises for leg extension (LE) and Low Row (LR). Specifically, in the SSG group, the parameters for LE were ($p = 0.0015$ and $ES = 2.28$ - Large), and the parameters for LR were ($p = 0.002$ and $ES = 1.95$ - Large). Moreover, in the PIG group, the parameters for LE were ($p = 0.009$ and $ES = 1.95$ - Large), and the parameters for LR were ($p = 0.0001$ and $ES = 2.88$ - Large). No differences were found between the groups (SSG_{post} vs. PIG_{post}). Both groups showed significant increases in flexibility but in different joints (SSG_{pre} vs. SSG_{post} ; PIG_{pre} vs. PIG_{post}). In the SSG group, only three joints showed significant increases in flexibility: shoulder extension ($p = 0.004$ and $ES = 1.76$ - Large), torso flexion ($p = 0.002$ and $ES = 2.36$ - Large), and hip flexion ($p = 0.001$ and $ES = 1.79$ - Large). In the PIG group, only three joints showed increases in flexibility: horizontal shoulder abduction ($p = 0.003$ and $ES = 2.07$ - Large), hip flexion ($p = 0.001$ and $ES = 2.39$ - Large), and hip extension ($p = 0.02$ and $ES = 1.79$ - Large). In-between group analyses ($SSG_{post} \times PIG_{post}$) revealed differences in two joints: shoulder extension ($p = 0.001$) and horizontal shoulder abduction ($p = 0.001$). Hormonal profiles showed no significant differences in cortisol secretion or growth hormone concentration. In conclusion, both studied strength protocols (with and without inter-set static stretching) resulted in flexibility and strength gains without an effect on the anabolic and catabolic hormonal profile.

Key words: strength performance, static stretching, cortisol, growth hormone, flexibility.

Introduction

Adequate levels of strength and flexibility are important for the promotion and maintenance of health and functional autonomy, as well as safe and effective sports participation (ACSM, 1998;

Simão et al., 2011). In this context, strength training (ST) is considered an integral component of a well-rounded exercise program, contributes to the treatment and prevention of injuries, and improves sports performance (ACSM, 2002; ACSM, 2009).

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The combinations of different types of stretching modes on athletic performance have been previously studied (Mikolajec et al., 2012; Shrier, 2004; Bacurau et al., 2009; Beckett et al., 2009; Little and Williams, 2006; Yamaguchi and Ishii, 2005; Behm et al., 2001; Dalrymple et al., 2010). All of these studies, with the exception of the study by Dalrymple et al. (2010), observed a decrease in explosive sport skills, such as sprinting and vertical jumps. However, Dalrymple et al. (2010) did not explain the influence of the two different stretching models (passive and dynamic stretching) on the countermovement jump.

Gomes et al. (2010) observed a decrease in the capacity to maintain force on strength training exercises before proprioceptive neuromuscular facilitation (PNF). In this study, static stretching did not affect endurance or strength performance.

Research has also demonstrated that a different inter-set rest interval length can produce different acute responses and chronic adaptations in neuromuscular and endocrine systems (Salles et al., 2009). However, little research has focused on the activity performed during these recovery periods (Caruso and Coday, 2008; Garcia-Lopez et al., 2010). It is common to see lifters performing ST inter-set stretching to improve the muscular recovery in sports or recreational-related exercises (Garcia-Lopez et al., 2010). Additionally, it has been suggested that inter-set stretching influences the time under tension and associated neuromuscular, metabolic, and/or hormonal systems. Recent data have shown that ST inter-set static stretching negatively affected the bench press acute kinematic profile compared with inter-set ballistic stretching and non-stretching conditions (Garcia-Lopez et al., 2010). In a chronic manner, static stretching performed before ST sessions resulted in similar strength gains to ST alone, suggesting that strength and stretching can be prescribed together to achieve optimal improvements in flexibility (Simão et al., 2011). Based on these results, the performance of inter-set static stretching may lead to additional improvements in flexibility levels and muscular recovery without additional time expended in the gym.

However, to date, only Simão et al. (2011) have observed the chronic effects of ST inter-set stretching on flexibility. Therefore, the aim of the

present study was to analyze the effects of eight weeks of strength training with and without inter-set static stretching on strength, flexibility and hormonal adaptations.

Material and Methods

Participants

The initial sample was composed of 16 trained men. All participants underwent a routine clinical evaluation. To be included in the experiment, volunteers had to meet the following criteria: (a) be trained for at least 24 months with a weekly frequency of three days; (b) agree to not perform any type of regular physical activity other than the prescribed strength training and flexibility training during the experiment; (c) be free from any condition that would influence the collection or interpretation of data; and (d) be free from the intake of ergogenic aids that could influence the collection or interpretation of the data. The 16 men were randomly assigned to 2 groups: the static stretching group (SSG; $n = 8$) or passive interval group (PIG; $n = 8$) (Table 1). Study details were explained verbally and in writing, and all participants signed an informed consent form before participation in the study in accordance with the declaration of Helsinki. The study protocol was approved by the Research Ethics Committee of the State University of Pará (Brazil).

Eight Repetition Maximum Test (8RM)

After a strength training familiarization period (4 sessions), all participants performed 2 familiarization sessions with the 8RM test protocol, with 72 hours between sessions. The 8RM tests were performed for the following exercises: machine bench press (BP), leg extension (LE), low row (LR), leg curl (LC), shoulder press (SP), and leg press (LP) (Techno Gym® - Gambettola, Italy) using a counterbalanced order. On day 1, the first 8RM test was performed, and then, after 72 hours, the 8RM test was repeated to determine test-retest reliability. The heaviest load achieved on the two test-retest days was considered the 8RM load. No exercise was allowed in the 72 hours between the 8RM tests. To minimize error during the 8RM tests, the following strategies were adopted (Simão et al., 2005; ACSM, 2010): (a) standardized instructions concerning the testing procedures were given to participants before the test; (b) participants

received standardized instructions on exercise technique; c) standard verbal encouragement was provided during the testing procedure; d) verbal stimuli were used to maintain a high exercise intensity; e) the additional weights used in the study were previously calibrated on a precision scale (Filizola, Brazil); f) for a repetition to be validated, a complete range of motion had to be performed. The 8RM was determined in fewer than 5 attempts, with a rest interval of 5 minutes between them; g) no pause was allowed between

the eccentric and concentric phase of a repetition or between repetitions, and the velocity was controlled with a metronome (Qwik Time Quartz Metronome, Evets Corp., Laguna Beach, CA) calibrated to 60 beats $\times$ min⁻¹.

After the 8 weeks of training, the 8RM test was performed with the same procedures of the pre-training test to observe the possible strength gains within and between groups. The 8RM tests were consistently conducted during the morning for each participant.

Table 1
*Characterization of the sample in pretraining situation. *t*

	SSG (n = 8)	P-value (SW)	PIG (n = 8)	P-value (SW)
Age (y)	22.13 $\pm$ 2.74	0.202	23.13 $\pm$ 1.55	0.731
Height (cm)	176.13 $\pm$ 1.65	0.423	176.88 $\pm$ 2.30	0.168
Body mass (kg)	81.00 $\pm$ 7.95	0.055	85.13 $\pm$ 7.90	0.356
% Body fat	12.88 $\pm$ 1.79	0.447	13.90 $\pm$ 1.90	0.823
BMI (Kg.m⁻²)	26.37 $\pm$ 2.00	0.341	27.18 $\pm$ 2.02	0.206

*Legend: PSS = Passive stretching group; PIG = Passive interval group;
BMI= Body mass index; SW = Shapiro-Wilk.*

Flexibility Measurement (Goniometry Protocol)

Flexibility was measured before and after 8 weeks of the experiment in 8 maximum stretching articular movements (ACSM, 2010). The flexibility measurements were taken 72 hours after the last 8RM test. The maximum flexibility measurement registered in 3 attempts with an interval of 10 seconds between attempts was considered for further evaluation (ACSM, 2011). The same procedure was executed post-training. All flexibility tests were conducted at the same time of the day. The data collected during the first evaluation were not made available to the evaluator to prevent information bias during measurements taken after training. Before the flexibility test, a warm-up was performed for the muscle groups involved in the evaluation. Two sets were used for the static stretching warm-up protocol, holding the position for 10 seconds in each set, until a point of slight discomfort was reached. A 10-second interval was provided between the warm-up stretching sets. The 8

maximum stretching articular movements were: a) shoulder flexion; b) shoulder extension; c) horizontal shoulder abduction; d) horizontal shoulder adduction; e) torso flexion; f) torso extension; g) hip flexion; and h) hip extension.

Blood Evaluations (Cortisol and Growth Hormone)

Both the SSG (n = 8) and PIG (n = 8) group participants underwent two blood collections: one at baseline and the second at the end of the eighth week of the exercise program. Blood was collected by a trained professional (approximately 5-ml blood samples from the antecubital vein) at 8 am to avoid the different concentrations of the hormonal circadian rhythm, with 12 h of rest. Blood samples were shipped in conditions suitable for laboratory analysis. Growth hormone was analyzed using the chemiluminescent enzyme immunometric method, while cortisol was analyzed using a chemiluminescent enzyme immunoassay.

Procedures

Before the 8-week training program (24 total sessions), 16 trained men were randomly assigned to 2 groups: the static stretching group (SSG; $n = 8$) and passive interval group (PIG; $n = 8$). The SSG and PIG groups performed 4 familiarization sessions with the exercises included in the training program. After familiarization with the exercises and before 8RM tests and retests, the subjects performed 2 sessions covering the 8RM procedures. Individuals performed the test and retest of 8RM, test and retest of flexibility and had their cortisol and growth hormone (GH) evaluated under the pre-test and post-test conditions. The baseline measurements of the hormonal responses, strength and flexibility tests were taken 72 hours apart. After the flexibility measurement, both groups underwent 8 weeks of training under the supervision of experienced fitness professionals. After the 8-week training program, flexibility, strength, and hormone concentrations were evaluated again.

Training Protocols

The training protocol for all groups included 3 weekly sessions on alternate days, for a total of 24 sessions. All 16 subjects completed the study. All sessions were supervised by experienced fitness professionals. Strength training was composed of 6 exercises executed in 4 sets with 8RM. The order established for the strength training was as follows: BP, LE, LR, LC, SP, and LP. Before each training session, the subjects executed a specific warm-up involving 15 repetitions with 50% of the load used in the first and second exercises of the sequence. The rest interval between sets was 2 min and included passive rest or static stretching exercises for the muscle involved in the ST exercises for the PIG and SSG group, respectively. Static stretching was performed at the point of mild discomfort, with stretches held for 30 seconds (ACSM, 2011). The rest interval between an exercise was 5 min.

The initial training loads were adjusted for all participants and increased when the volunteers were able to perform more than 8RM by readjustment of 5% of the initial loads. All testing and training sessions were performed in the morning hours and were consistent throughout the study. To protect against bias, the investigators that conducted the training program

did not conduct the testing measurements, and the staff involved in the strength and flexibility tests were blinded to the group assignment.

Statistical Analyses

The statistical analysis was initially performed using the Shapiro–Wilk normality test and homoscedasticity test (Bartlett criterion). As mentioned, the 8RM tests were found to be similar when tested on two occasions prior to performing the different sequences. To compare the differences between and within groups in pre-training and post-training tests, ANOVA with repeated measures was performed ($SSG_{pre} \times SSG_{post}$; $PIG_{pre} \times PIG_{post}$; $SSG_{post} \times PIG_{post}$). An alpha level of $p < 0.05$ was considered statistically significant for all comparisons. All statistical analyses were conducted using SPSS statistical software package, version 20.0 (SPSS Inc., Chicago, IL). The calculation of effect size (the difference between pretest and posttest scores divided by the pretest standard deviation) and scale proposed by Rhea (2004) were used to examine the magnitude of any treatment effect.

Results

Strength Results

The results obtained show an intraclass coefficient of SSG group: BP = 0.97; LE = 0.97; LR = 0.93; LC = 0.98; SP = 0.99; LP = 0.98 and in PIG group: BP = 0.96; LE = 0.98; LR = 0.80; LC = 0.94; SP = 0.97; LP = 0.98. A paired-samples t-test was performed and did not demonstrate any significant difference ($p < 0.05$) between 8RM tests on separate testing occasions. Both groups showed significant increases in strength (SSG_{pre} vs. SSG_{post} ; PIG_{pre} vs. PIG_{post}), in same exercises; LE and LR. In SSG group in LE ($p = 0.0015$ and $ES = 2.28$ - Large) and LR ($p = 0.002$ and $ES = 1.95$ - Large) and in PIG group in LE ($p = 0.0090$ and $ES = 1.95$ - Large) and in LR ($p = 0.0001$ and $ES = 2.88$ - Large).

No differences were showed between groups (SSG_{post} vs. PIG_{post}). All results are presented in Table 2.

Flexibility Measurements

Both Groups showed significant increases in flexibility, but in different joints (SSG_{pre} vs. SSG_{post} ; PIG_{pre} vs. PIG_{post}). In SSG Group, only three joints showed significant increases in flexibility: shoulder extension ($p = 0.004$ and $ES =$

1.76 - Large); torso Flexion ($p = 0.002$ and $ES = 2.36$ - Large) and hip flexion ($p = 0.001$ and $ES = 1.79$ - Large). In PIG group, only three joints showed increases in flexibility: horizontal shoulder abduction ($p = 0.003$ and $ES = 2.07$ - Large); hip flexion ($p = 0.001$ and $ES = 2.39$ - Large) and hip extension ($p = 0.02$ and $ES = 1.79$ - Large).

In between groups analyses ($SSG_{post} \times PIG_{post}$) differences were found only in two joints: shoulder extension ($p = 0.001$) and horizontal

shoulder abduction ($p = 0.001$). All results are presented in Table 3.

Hormone profile

The results showed no significant differences in the concentration of cortisol and growth hormone (Table 4 - $p > 0.05$). Effect size data demonstrated trivial results in both hormones in SSG and PIG group (pretest vs. posttest).

Discussion

The purpose of the present study was to analyze the effects of eight weeks of ST in 2 experimental groups (SSG and PIG) with and without inter-set static stretching on strength, flexibility and hormone profile of trained men. It was hypothesized that ST performed with inter-set static stretching would not result in additional strength and flexibility and also not change the anabolic-catabolic hormone profile after 24 weeks of training. The key finding of the present study was that both training groups presented significant strength and flexibility gains after 24 weeks and showed no differences in the anabolic-catabolic hormone profile, which confirmed the initial hypothesis. Additionally, the inter-set static stretching ST group demonstrated larger strength gains in two exercises and larger flexibility gains in three joints compared with ST alone. However, the results revealed a significant increase in muscle strength for only a few exercises in the SSG (LP, LR) and PIG (LR) experimental conditions.

Table 2
Strength results at baseline and posttraining situation in 8RM test

SSG				
	Pre	Post	ES	
Shoulder Flexion	157.38 ± 7.67	169.13 ± 7.84	1.05	Moderate
Shoulder Extension	34.88 ± 4.20	42.25 ± 4.52*†	1.76	Large
horizontal shoulder abduction	35.63 ± 8.15	43.25 ± 8.84†	0.93	Moderate
horizontal shoulder adduction	112.38 ± 6.52	119.63 ± 6.16	1.11	Moderate
torso flexion	71.88 ± 6.08	86.25 ± 9.32*	2.36	Large
torso extension	19.63 ± 5.04	26.00 ± 5.12	1.26	Moderate
hip flexion	73.25 ± 3.77	96.00 ± 7.52*	6.03	Large
hip extension	14.50 ± 3.89	20.38 ± 5.07	1.48	Moderate
PIG				
Shoulder Flexion	160.252 ± 9.59	166.25 ± 10.18	0.62	Small
Shoulder Extension	29.25 ± 7.65	31.75 ± 5.82†	0.32	Trivial
horizontal shoulder abduction	26.50 ± 1.70	30.00 ± 2.20††	2.07	Large
horizontal shoulder adduction	114.50 ± 4.10	118.00 ± 3.62	0.85	Moderate
torso flexion	71.75 ± 9.62	79.25 ± 12.39	0.78	Trivial
torso extension	16.13 ± 2.99	20.38 ± 3.16	1.41	Moderate
hip flexion	76.38 ± 7.05	93.25 ± 7.99†	2.39	Large
hip extension	13.88 ± 1.95	17.38 ± 3.02†	1.78	Large

* - Significant difference between pretraining situation and posttraining in SSG.

† - Significant difference between pretraining situation and posttraining in PIG.

Table 3

Flexibility results at baseline and posttraining situation

SSG				
	<i>Pre</i>	<i>Post</i>	<i>ES</i>	
Bench Press	77.88 ± 7.43	88.25 ± 7.48	1.4	Moderate
Leg Extension	81.88 ± 9.98	104.63 ± 13.14*	2.28	Large
Low Row	86.25 ± 10.26	106.25 ± 11.58*	1.95	Large
Leg Curl	55.38 ± 11.00	66.25 ± 9.91	0.99	Small
Shoulder Press	70.25 ± 9.14	79.50 ± 8.40	1.01	Small
Leg Press	225.63 ± 44.84	280.63 ± 48.43	1.22	Moderate
PIG				
Bench Press	76.38 ± 6.34	84.13 ± 6.37	1.22	Moderate
Leg Extension	76.00 ± 9.44	94.50 ± 14.48†	1.95	Large
Low Row	90.13 ± 5.87	107.00 ± 7.50†	2.88	Large
Leg Curl	51.63 ± 11.40	58.63 ± 13.39	0.61	Small
Shoulder Press	66.63 ± 11.55	73.13 ± 12.49	0.56	Small
Leg Press	233.13 ± 44.95	279.38 ± 45.62	1.03	Moderate

* - Significant difference between pretraining situation and posttraining in SSG.

† - Significant difference between pretraining situation and posttraining in PIG.

‡ - Significant difference between groups in posttraining situation.

Table 4

Hormones responses results at baseline and posttraining situation

Table 4. Hormones responses results at baseline and posttraining situation.

	SSG			PIG		
	<i>Pre</i>	<i>Post</i>	<i>ES</i>	<i>Pre</i>	<i>Post</i>	<i>ES</i>
Cortisol	16.71 ± 5.15	15.70 ± 5.55	0.20 - Trivial	13.64 ± 5.61	14.39 ± 5.3	0.13 - Trivial
Growth Hormone	0.18 ± 0.14	0.27 ± 0.20	0.09 - Trivial	0.15 ± 0.13	0.19 ± 0.09	0.04 - Trivial

No Significant difference between pretraining situation and posttraining in SSG.

No Significant difference between pretraining situation and posttraining in PIG.

No Significant difference between pretraining situation and posttraining in SSG.

No Significant difference between pretraining situation and posttraining in PIG.

This indicates that stretching between sets does not compromise increases in strength achieved by resistance training. Inter-set static stretching significantly changed the strength of LE in the SSG group and LR in both groups. These findings are consistent with previous studies on this issue (Nelson et al., 2005; Bacurau et al., 2009; Gomes et al., 2011) and indicate that stretching does not modify the strength gains promoted by resistance training. These findings have

potentially important implications for strength and conditioning professionals who may commonly use stretching exercises as an integral part of a warm-up routine or during the training session itself. Perhaps, these results could be applied to the resistance training protocol with a long-term rest interval, 2 minutes between sets and 5 minutes between exercises and high loads with 8RM.

To our knowledge, this is the first study

that analyzed the chronic effects of inter-set stretching. However, previous studies have analyzed the chronic effects of pre- (Simão et al., 2011) or post-ST (Nóbrega et al., 2005) stretching on strength and flexibility gains. Nevertheless, the effect size in the current study showed that strength training with stretching inter-set intervals increases flexibility in previously recreationally trained men, and strength and flexibility can be prescribed together to achieve better flexibility results. Indeed, Simão et al. (2011) analyzed strength and flexibility gains achieved through isolated or simultaneous strength and flexibility training in adult sedentary women. The sedentary women were randomly assigned to ST, flexibility training, the combination of both, or a control group. All of the groups performed pre- and post-training sit and reach tests to verify the flexibility level and 10RM tests for leg press and bench press exercises. The training protocol for all of the groups, except for the control group, was composed of three sets of eight exercises for upper and lower limbs three times per week. The flexibility training was composed of static stretching exercises that involved the upper and lower limbs performed before ST sessions. The results showed that the ST, ST + flexibility, and flexibility groups had significantly increased flexibility compared with baseline and the control group. The strength tests demonstrated that ST and ST + flexibility significantly increased 10RM when compared with baseline flexibility and the control group. The authors suggested that strength and flexibility can be prescribed in the same session to increase flexibility to a greater extent. Similar to our findings, the strength and flexibility training group presented larger flexibility gains than the ST alone group; however, there were no additional strength gains when compared with the ST alone group. Kokkonen et al. (2007) conducted research to verify the differences in lower limb strength gains in physically active individuals by comparing strength training in isolation versus strength training combined with static stretching exercises for the hip, thigh muscles and plantar flexors. They found significant strength increases in the lower limbs for both groups. However, the greatest differences were observed in the group that performed strength training in combination with stretching exercises (16%, 27% and 31% in

the 1RM test for knee flexion, knee extension, and leg press exercises, respectively). The data from our study showed an increase of 27.79% in the knee extension exercise in the SSG group, which was in agreement with the study by Kokkonen et al. (2007). Moreover, the present study showed that increases in strength could be observed in the SSG group in the LR with an increase of 23.19% in the 8RM test; the PIG group demonstrated increases in strength in the LR (18.72%) in the 8RM test.

Mohamad et al. (2011) reported that stretching between sets of ST could increase muscle hypertrophy and suggested the possibility of additional increases in muscle strength in relation to strength training alone. However, it is important to emphasize that our study did not assess muscle hypertrophy, but only one anabolic growth hormone and one catabolic hormone (cortisol). These hormones showed no significant differences between pre- and post-ST evaluations between the groups. It is also important to note that the inclusion of stretching during intervals between sets did not reduce the gains at the end of the experiment or the intensity at which our participants were able to train. There are multiple studies that have suggested acute strength impairments following the performance of static stretching. This phenomenon could easily have affected chronic adaptations and daily session loading.

Any decrease in the acute training load could have contributed to the differing amounts of strength gains between the groups. Nóbrega et al. (2005) investigated the interaction of ST and flexibility training in young sedentary men and women. The subjects followed an ST protocol with intensities initially set at 60% of 1RM which was continuously adjusted so that fatigue was achieved after 8-12 repetitions. Static stretching exercises were performed after the ST sessions. At the end of 12 weeks, the authors verified that resistance training improved muscle strength either alone or in combination with flexibility training; however, ST alone did not change flexibility. Flexibility increased with specific training alone or in combination with ST. Similar to Simão et al. (2011) and our results, Nóbrega et al. (2005) found strength gains with ST alone and in combined strength and flexibility training groups.

In our study, the finding that larger strength increases in two exercises were observed in the inter-set stretching group is new. Previous literature has not presented larger strength gains with the inclusion of stretching exercises in a ST routine, which may be related to the fact that the static stretching exercises were performed between sets. Inter-set stretching will influence the time under tension and the associated neuromuscular, metabolic, and/or hormonal responses (Mohamad et al., 2011), which are related to the larger strength improvements presented by the inter-set stretching group.

The increased time under tension increases the effect of various neuromechanical and metabolic stimuli that are thought to be important for hypertrophic adaptation (Mohamad et al., 2011). It has been suggested that during ischemic conditions, such as during inter-set stretching, metabolites and ions accumulate rather than dissipate, which in turn leads to GH secretion and increased levels of IGF-1 (Mohamad et al., 2011). The limitations of our study include no inclusion of a control group, the short

experimental period, and reduced adaptation to ST in the trained sample.

Conclusions and Practical Implications

In conclusion, both studied ST protocols (with and without inter-set static stretching) resulted in flexibility and strength gains without influencing the anabolic-catabolic hormone profile. However, the results suggest that inter-set static stretching can be adopted to achieve additional strength and flexibility gains. Future studies analyzing the flexibility and strength gains in response to different inter-set stretching strategies, longer intervention periods, and different samples are necessary to confirm the results. Further research is also necessary to verify the effects of these strategies on hypertrophic adaptation, as previously suggested.

The results of the present study indicate that inter-set static stretching leads to additional improvements in strength and flexibility without additional time expended in the gym. The time saved by omitting separate stretching routines may help increase adherence to training by recreational fitness practitioners who have limited exercise time.

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Game Performance Versus Competitive Performance in the World Championship of Handball 2011

by
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This article assesses the game performance of the teams participating in the Men's World Championship of Handball of 2011 by using Data Envelopment Analysis (DEA) and the cross-efficiency evaluation. DEA uses Linear Programming to yield a measure of the overall performance of the game of particular teams, and allows us to identify relative strengths and weaknesses by means of benchmarking analysis. The cross-efficiency evaluation provides a peer-appraisal of the teams with different patterns of game, and makes it possible to rank them. Comparisons between this ranking and the final classification in the championship provide an insight into the game performance of the teams versus their competitive performance. We highlight the fact that France, which is the world champion, is also identified as an "all-round" performer in our game performance assessment.

Key words: team game performance, Data Envelopment Analysis, cross-efficiency evaluation, handball.

Introduction

Tactics are considered an important aspect of team sports, which can be expressed individually or collectively. The collective strategic behaviour is often understood as the sum of individual behaviours, thus tactical decisions are sometimes evaluated individually as a way of evaluating collective tactics. The collective game in team sports is developed by taking into account the characteristics of the team's own players and the need to counteract the quality of the players of the opposing team. The achievement of high team performance depends on several factors such as technical skills, physical fitness or relationships between players. This is a complex system that is constantly changing and cannot be controlled by means of external fixed criteria, so regulatory mechanisms of dynamical systems can facilitate this task.

Tactical assessment can be made on the basis of either real matches or scrimmage games,

with the purpose of evaluating specific aspects of tactical decisions of the players. Nevertheless, the assessment of tactics in real matches is very important, because there are situations that only arise in the context of real game and these would be difficult to reproduce in scrimmage conditions. Extensive literature deals with tactical performance evaluation in team sports based on tactical indexes. There are several articles that are intended to determine which indexes are more representative or which may be more significant for the analysis of tactics. See the investigations in football (Tenga et al., 2010a, 2010b, 2010c), basketball (Swalgin, 1998; Trninic and Dizdan, 2000; Trninic et al., 2000) and water polo (Hraste et al., 2008).

There are also some works focusing on different strategies, approaches and styles of the teams, which may lead to different tactical indexes. It is argued that the analysis of the different groups formed in the preliminary stages of the Handball World Championship 2003

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generated different indicators of success taking into account the reference groups and the different characteristics of each team (Gruic et al., 2006). This suggests that we should not use a unique pre-established pattern of game that is imposed to all the teams in their assessments. Instead, we should use a model that somehow takes into consideration the characteristics of the game of each team. This is why we propose the use of "Data Envelopment Analysis" (DEA) (Charnes et al., 1978) for the assessment of team game performance.

To define a measure of the overall team performance in the game we must determine how the variables that describe the different aspects of the game have to be aggregated. In order to do so, we need to specify the importance (the weight) that is to be attached to each of these aspects of the game. Traditionally, teams are assessed on the basis of a common set of weights. However, in this traditional approach the choice itself of the weights often raises serious difficulties, and in many cases the analysts do not agree upon the weights to be used. In DEA there is no need to know such weights beforehand. The weights are determined trying to show the team under assessment in its best possible light. Besides, the DEA weights are team-specific, so this methodology provides a self-evaluation in which each team can exploit its strengths in the assessments. As another interesting feature of this methodology, we point out that with DEA we may develop plans for improvement of the game by means of benchmarking analysis. The teams are classified into efficient and inefficient, so the latter are assessed with respect to the former. DEA allows us to identify the weaknesses in the game of the inefficient teams and to set efficient targets, which represent levels of performance in each aspect of the game that would make each of them perform efficiently. Like the DEA weights, the targets are also team-specific. These targets result from the selection of a benchmark that is made taking into consideration the type of the game of the team under assessment. The key issue is that each team may have a different way to achieve the efficiency, which will obviously depend on the characteristics of its game. However, the main weakness of DEA is perhaps the fact that it cannot provide a ranking of teams based on the measures of efficiency it yields since,

as said before, the score of each team is calculated with weights that are usually different from those of the others. For this reason, we also propose here the use of the cross-efficiency evaluation (Sexton et al., 1986; Doyle and Green, 1994), which is an extension of DEA aimed at providing a ranking. The idea behind the cross-efficiency evaluation is to assess each team with the DEA weights of all the teams instead of with only its own weights. This provides a peer-appraisal of the game performance of the teams with different patterns of game and, in addition, we can rank the teams according to the resulting cross-efficiency scores.

DEA has been successfully used in public and private sectors and, in particular, in the context of sports. For instance, Cooper et al. (2009) assess basketball players by using the statistics of the Spanish premier league. Cooper et al. (2011) provide a ranking of basketball players with a cross-efficiency evaluation. DEA and cross-efficiency evaluation are combined for the assessment and ranking of professional tennis players (Ruiz et al., 2011). Ramón et al. (2012) also rank tennis players with a common set of weights obtained from DEA weights. See also the evaluations of players by using DEA in baseball (Anderson and Sharp, 1997; Chen and Johnson, 2010; Sexton and Lewis, 2003; Sueyoshi et al., 1999), golf (Fried et al., 2004; Fried and Tauer, 2011; Ueda and Amatatsu, 2009) and football (Alp, 2006).

DEA has been used not only for the assessment of players. See, for example, the case of soccer, where we can find evaluations of teams (Boscá et al., 2009; Espitia-Escuer and García-Cebrián, 2004; García-Sánchez, 2007; González-Gómez and Picazo-Tadeo, 2010; Haas, 2003; Haas et al., 2001), coaches (Dawson et al., 2000) and clubs (Barros et al., 2010). At the level of countries, DEA has been used for measuring the performance of the participating nations at the Summer Olympics Games (Lozano et al., 2002; Soares de Mello et al., 2009; Wu et al., 2010; Zhang et al., 2009).

Finally, we can also find applications of DEA analyzing the efficiency in sports from other perspectives. Fazel and D'Itri (1999) study the impact on organizational performance of practices like firing and hiring managers. Volz (2009) provides efficiency scores not only of team

concerned with defense cannot be larger than that of those regarding the offensive aspects of the game.

By virtue of the duality theory in linear programming, DEA also provides a benchmarking analysis by solving the following model

$$\begin{aligned} &\text{Maximize} && \phi_0 \\ &\text{subject to:} && \\ &&& \lambda_1 \times P_1 + \dots + \lambda_{24} \times P_{24} \geq \phi_0 \times P_0 \\ &&& \lambda_1 + \dots + \lambda_{24} = 1 \\ &&& \lambda_1, \dots, \lambda_{24} \geq 0 \end{aligned} \quad (2)$$

The optimal value of (2), ϕ_0 , is actually the inverse of θ_0 in (1). Therefore, team 0 is efficient if $\phi_0 = 1$, while it is rated as inefficient if $\phi_0 > 1$. Figure 1 illustrates graphically the idea behind model (2). Suppose that we have 3 handball teams that are to be assessed regarding two game factors, say, G6m and G9m. Their records in the championship in these two variables are $P_1(2,7)$ for team 1, $P_2(10,3)$ for team 2 and $P_3(4,3)$ for team 3, i.e., team 1, for example, scored 2 6m goals per game and 7 9m goals per game, and so on. The grey area is the so-called production possibility set (PPS), and includes the teams (real or virtual) that are assumed to be potential benchmarks in the assessments. Roughly speaking, in the PPS we have combinations of real teams, and others that represent worse performances. The points on the frontier of the PPS (the bold line) represent obviously “best practice” performances. Teams 1 and 2 are rated as efficient because we cannot find in the PPS other teams that score more 6m goals and more 9m goals than them. In that case, ϕ_1 and ϕ_2 cannot be greater than 1. However, team 3 is inefficient because other teams in the PPS outperform it regarding these two game factors. In particular, the point $(6.4, 4.8)$ shows that team 3 should score 6.4 6m goals and 4.8 9m goals in order to perform at the levels of the efficient teams (these are actually the targets for team 3). In other words, $\phi_3 = 1.60$ is the efficiency score of team 3, which means that it should improve by 60% in these two game factors. The point $(6.4, 4.8)$ is a benchmark for team 3 that results from a combination of team 1 and team 2 in which the participation of the former is 45% and that of

latter is 55%, i.e., $\lambda_1=0.45$ and $\lambda_2=0.55$ in model (2) (obviously, $\lambda_3=0$), so that

$$\begin{pmatrix} 6.4 \\ 4.8 \end{pmatrix} = 0.45 \times P_1 + 0.55 \times P_2.$$

Figure 1
Graphical explanation of model (2)

Finally, we use the cross-efficiency evaluation for the ranking of teams. The cross-efficiencies of team 0 are the assessments of this team with the weights of the others. That is, if $(\omega_1^d, \dots, \omega_8^d)$ are the weights of team d, obtained by solving (1) for that team, then the cross-efficiency

$$E_{d,0} = \frac{1}{\omega_1^d \times y_{1,0} + \dots + \omega_8^d \times y_{8,0}} \quad (3)$$

is an evaluation of team 0 with the weights of team d. The cross-efficiency score of team 0 is the average of such cross-efficiencies, i.e.,

$$\bar{E}_0 = \frac{1}{24} (E_{1,0} + \dots + E_{24,0}) \quad (4)$$

The cross-efficiency scores provide thus a peer-appraisal in which each team is assessed with reference to the different patterns of game that the different teams have used in their DEA assessments, and also determine a full ranking of teams.

For those readers interested in details on the DEA models, their formulations and properties, see the textbook by Cooper et al. (2007).

Results

The DEA model revealed that 9 out of the 24 teams participating in the championship were efficient. For each of them, Table 1 records the contributions to the efficiency of each game factor. These contributions, which are called “virtual weights”, are the product of the absolute weights and the corresponding actual values, i.e., for team 0 these would be $\omega_r \times y_{r0}$, $r=1,\dots,8$, where the ω 's are the weights provided by (1) when solved for that team. They are dimensionless and represent the percentages of contribution of each factor to the total efficiency (100%), so they can be seen as the relative importance attached to each aspect of the game in the assessment of each team. This table also reports the number of times each of the efficient teams acted as referent in the assessment of the inefficient ones, which is determined as the number of times the corresponding λ_j in model (2) is non-zero in the assessment of the different teams.

The benchmarking analysis provided by DEA is reported in Table 2. For each inefficient team, in this table we have its actual data (in the first row of each team) and the corresponding efficient targets (in the second row). The third row records the difference between the target and the

actual data in relation to the actual data. Large values of these percentages may suggest the need of the team under assessment for improvement in the corresponding aspect of the game. Table 2 also reports which efficient teams compose the benchmark used in the assessments, together with their contributions as efficient referents in such benchmark, i.e., the λ_j 's provided by model (2).

Table 3 records the cross-efficiencies (3) and the cross-efficiency scores (4). We note that in our analysis we used a variant of the standard cross-efficiency evaluation that assesses the teams by only using the weights of those that have been rated as efficient in the DEA self-evaluation (Ramón et al., 2011). Thus, the rows of this table correspond to each of the teams participating in the championship, and in each of them we have the evaluations of their game (the cross-efficiencies) with the weights of each of the efficient teams (under the corresponding column). The last column of the table shows the cross-efficiency scores and in brackets their corresponding rankings. We can see, for instance, that France ranks 1st followed by Spain, Denmark and Slovakia, in this order. The teams in the rows of the table appear in order of the final classification of the world championship, so we can make comparisons between the two rankings.

Table 1
Efficient teams: Contributions to the efficiency and number of times acting as referent

TEAM	G6m	Gwing	G9m	G7m	Gfastb	Gbt	Rec	Bloc	total	#ref.
FRA	11.04%	11.04%	11.04%	13.38%	13.38%	13.38%	13.38%	13.38%	100.00%	13
DEN	22.79%	22.79%	22.79%	6.32%	6.32%	6.32%	6.32%	6.32%	100.00%	9
SPA	6.32%	14.40%	6.32%	26.99%	6.32%	6.32%	26.99%	6.32%	100.00%	13
CRO	5.28%	23.80%	5.28%	24.90%	5.28%	24.90%	5.28%	5.28%	100.00%	2
ICE	3.13%	3.13%	3.13%	3.13%	40.61%	3.13%	40.61%	3.13%	100.00%	5
HUN	1.95%	1.95%	1.95%	35.42%	48.64%	1.95%	1.95%	6.18%	100.00%	0
NOR	68.03%	1.80%	1.80%	1.80%	1.80%	1.80%	1.80%	21.17%	100.00%	6
KOR	6.64%	1.18%	1.18%	54.79%	1.18%	32.65%	1.18%	1.18%	100.00%	0
SVK	34.46%	8.43%	4.75%	33.39%	4.75%	4.75%	4.75%	4.75%	100.00%	4

Table 2
Benchmarking analysis: Actual data and efficient targets (inefficient teams)

TEAM	G6m	Gwing	G9m	G7m	Gfastb	Gbt	Rec	Bloc	Benchmarks
SWE	2.44	2.50	3.30	1.58	3.29	3.31	3.50	2.90	FRA(28.56%),SPA(24.23%),
	3.42	2.93	4.05	2.33	3.86	3.88	4.11	4.14	DEN(17.45%),CRO(29.77%)
	40.37%	17.35%	22.83%	47.87%	17.35%	17.35%	17.35%	42.90%	
POL	4.12	1.61	3.58	1.88	4.20	2.48	4.00	4.11	FRA(48.94%),SPA(6.91%),
	4.30	1.92	4.47	2.12	4.38	2.91	4.17	4.28	NOR(43.14%),ICE(1.01%)
	4.22%	18.83%	24.74%	12.66%	4.22%	17.15%	4.22%	4.22%	
SRB	2.50	3.13	4.27	2.03	2.24	2.79	2.11	3.11	FRA(23.78%),SPA(24.20%),
	3.57	3.44	4.69	2.23	4.09	3.07	3.99	4.11	DEN(45.72%),CRO(6.31%)
	42.76%	9.82%	9.82%	9.82%	82.63%	9.82%	89.11%	32.12%	
GER	3.88	2.63	4.71	1.46	2.86	2.73	4.00	3.33	FRA(43.24%),SPA(13.24%),
	3.94	2.67	4.78	2.14	4.32	3.12	4.06	4.29	DEN(24.19%),NOR(19.33%)
	1.44%	1.44%	1.44%	46.71%	50.75%	14.14%	1.44%	28.77%	
ARG	2.43	2.02	2.28	2.13	3.46	3.11	4.11	2.89	FRA(47.24%),SPA(43.70%),
	3.40	2.38	4.30	2.52	4.09	3.68	5.01	3.87	DEN(8.11%),ICE(0.95%)
	40.29%	18.24%	88.04%	18.24%	18.24%	18.24%	21.86%	34.05%	
EGY	2.60	3.18	2.30	1.72	2.48	1.68	3.29	2.71	SPA(36.05%),DEN(63.95%)
	3.54	3.93	4.53	2.31	3.93	2.26	4.06	3.79	
	35.74%	23.61%	96.99%	34.06%	58.75%	34.30%	23.61%	39.53%	
ALG	2.55	1.50	2.62	0.57	2.10	1.98	3.29	2.14	FRA(31.80%),SPA(39.55%),
	3.79	2.23	3.89	2.49	4.00	2.95	4.88	3.73	DEN(3.69%),NOR(21.87%),
	48.53%	48.53%	48.53%	336.20%	90.39%	48.53%	48.53%	74.15%	SVK(3.09%)
JPN	2.22	2.15	1.76	0.86	4.71	3.62	3.00	1.29	FRA(63.88%),DEN(13.90%),
	3.70	2.27	5.13	1.98	4.96	3.81	4.13	4.24	ICE(22.22%)
	66.69%	5.21%	191.49%	129.84%	5.21%	5.21%	37.79%	229.42%	
AUT	3.72	1.26	4.52	1.56	4.99	2.04	3.29	4.29	FRA(75.54%),NOR(2.79%),
	3.73	1.87	5.09	2.01	4.99	4.11	4.31	4.29	ICE(21.67%)
	0.14%	48.71%	12.65%	29.53%	0.14%	101.51%	31.28%	0.14%	
ROU	2.57	1.80	4.02	2.03	3.65	2.54	4.57	4.00	FRA(69.66%),SPA(30.34%)
	3.49	2.09	4.67	2.39	4.31	4.26	4.84	4.23	
	35.85%	16.31%	16.18%	17.66%	18.22%	67.84%	5.81%	5.81%	
TUN	3.11	2.11	3.11	1.08	2.16	1.66	3.00	3.00	FRA(17.98%),SPA(17.10%),
	4.15	2.82	4.33	2.18	4.13	2.21	4.00	4.00	DEN(29.12%),NOR(34.35%),
	33.45%	33.45%	39.30%	102.06%	91.19%	33.45%	33.45%	33.45%	SVK(1.45%)
BRA	4.13	3.36	2.06	2.24	2.67	2.48	3.57	3.14	SPA(16.38%),DEN(38.52%),
	4.18	3.41	3.46	2.27	4.09	2.83	3.91	3.49	SVK(45.11%)
	1.34%	1.34%	68.12%	1.34%	53.15%	14.31%	9.60%	11.05%	
CHI	2.17	1.75	1.81	1.17	3.34	3.19	5.00	2.29	FRA(37.89%),SPA(62.11%)
	3.26	2.25	3.81	2.75	3.85	3.51	5.50	3.53	
	50.55%	28.40%	110.76%	135.47%	15.30%	10.09%	10.09%	54.59%	
BRN	1.79	0.76	2.62	1.60	3.84	2.50	3.86	1.43	FRA(40.11%),SPA(22.70%),
	3.50	1.93	4.26	2.24	4.87	3.17	4.89	3.40	ICE(37.20%)
	96.04%	155.65%	62.75%	40.57%	26.82%	26.82%	26.82%	138.33%	
AUS	1.72	0.87	1.54	1.61	1.33	1.52	2.86	1.14	FRA(6.64%),SPA(83.55%),
	3.22	2.41	2.89	3.01	3.48	2.84	5.93	2.88	NOR(0.99%),SVK(8.81%)
	87.42%	176.56%	87.42%	87.42%	161.13%	87.42%	107.65%	152.38%	

Table 3

Cross-efficiency evaluation.

TEAM	TEAM providing weights									score (ranking)
	FRA	DEN	SPA	CRO	ICE	HUN	NOR	KOR	SVK	
FRA	1	1	1	1	1	1	1	1	1	1 (1)
DEN	1	1	1	1	1.20	1.09	1.08	1.34	1	1.07 (2)
SPA	1.08	1.21	1	1.03	1.00	1	1.38	1	1	1.07 (2)
SWE	1.32	1.38	1.30	1.28	1.33	1.38	1.52	1.40	1.37	1.37 (17)
CRO	1.09	1.15	1.08	1	1.27	1.15	1.11	1	1.08	1.10 (5)
ICE	1.22	1.27	1.21	1.34	1	1	1.36	1.50	1.18	1.23 (9)
HUN	1.24	1.39	1.23	1.28	1.10	1	1.50	1.28	1.26	1.25 (11)
POL	1.20	1.22	1.20	1.28	1.16	1.14	1.08	1.32	1.12	1.19 (6)
NOR	1.22	1.20	1.22	1.38	1.23	1.13	1	1.50	1.04	1.21 (8)
SRB	1.32	1.32	1.28	1.20	1.71	1.40	1.50	1.29	1.24	1.36 (16)
GER	1.21	1.16	1.19	1.24	1.27	1.44	1.16	1.45	1.17	1.26 (13)
ARG	1.31	1.45	1.27	1.26	1.24	1.22	1.54	1.24	1.30	1.31 (15)
KOR	1.33	1.39	1.29	1.18	1.31	1.10	1.42	1	1.15	1.24 (10)
EGY	1.41	1.51	1.36	1.37	1.53	1.51	1.61	1.62	1.39	1.48 (18)
ALG	1.90	1.83	1.88	2.07	1.74	2.45	1.77	2.58	2.01	2.03 (23)
JPN	1.56	1.65	1.60	1.53	1.32	1.45	1.87	1.77	1.82	1.62 (20)
SVK	1.10	1.14	1.10	1.08	1.12	1.05	1	1.07	1	1.07 (2)
AUT	1.26	1.26	1.29	1.41	1.19	1.13	1.16	1.53	1.21	1.27 (14)
ROU	1.22	1.30	1.18	1.26	1.15	1.18	1.39	1.31	1.22	1.25 (11)
TUN	1.59	1.55	1.58	1.68	1.70	1.91	1.45	2.03	1.55	1.67 (21)
BRA	1.19	1.24	1.16	1.14	1.36	1.25	1.14	1.22	1.08	1.20 (7)
CHI	1.48	1.61	1.43	1.51	1.20	1.57	1.74	1.66	1.68	1.54 (19)
BRN	1.70	1.83	1.64	1.70	1.35	1.40	2.21	1.63	1.70	1.68 (22)
AUS	2.29	2.44	2.12	2.15	2.21	2.13	2.63	1.93	1.98	2.21 (24)

Discussion

On many occasions, tactics are validated on the basis of the achievement of victory, the winning team being rated as the best. However, we should not close the door to the analysis of other teams whose performance can serve as a model of efficiency for the game. For example, Table 1 shows that the 9 efficient teams achieved the efficiency with different patterns of game. We can see that France used a pattern of game in which all of the factors considered have the same importance. This shows a good performance of France in all of the aspects of the game. Denmark and Spain needed to put more weight in some of the game factors in order to be rated as efficient. Table 1 reveals that Denmark exploited to some extent its relative strength in G6m, Gwing and

G9m in the achievement of the efficiency (with a contribution to the efficiency of 22.79%), while Spain did the same with Gwing (14.40%), G7m and Rec (both with a contribution of 26.99%). We can also see in this table that these three teams played an important role as benchmarks for the remaining players: they acted as referents in the assessments of 13, 9 and 13 inefficient teams, respectively.

In contrast, other teams like Iceland, Hungary, Norway and Korea achieved the efficiency with a very specialized pattern of game. See, in particular, the case of Norway, whose efficiency was due mainly to exploiting its good performance in G6m (with a contribution to the efficiency of 68.03%), or that of Korea, which exploited to a large extent its behavior in G7m (54.79%), and also in Gbt (32.65%). We also note

that neither Korea nor Hungary were referents for any of the inefficient teams.

Concerning the inefficient teams, Table 2 provides useful information for benchmarking purposes. For example, we can see that Germany is very similar to its benchmark, which is a virtual team determined mostly by France (43.24%) and Denmark (24.19%) (also by Spain and Norway with a less relevant role). Its actual data are very close to the targets provided in most of the aspects of the game. However, the DEA model identifies three areas for potential improvement: G7m, where the actual data is 1.46 whereas the corresponding target is 2.14, which gives rise to a potential of improvement of 46.71%; Gfastb, where it is needed a raise from the actual 2.86 to the target 4.32 which means an improvement of 50.75%; and also in Bloc, where the percentage of improvement is 28.77%. Poland, whose benchmark is mainly determined by France (48.94%) and Norway (43.14%), also shows a good performance in several of the factors of the game, while at the same time there is some room for improvement in other factors like G9m, Gwing, Gbt and G7m. That could be also the case of Austria or Brazil, but for these teams some important weaknesses are detected: in Gbt for Austria, with a percentage of improvement of 101.51%, and in G9m (68.12%) and in Gfastb (53.15%) for Brazil. Finally, teams like Australia or Algeria exhibit a poor performance in practically all of the aspects of the game.

As for the cross-efficiency evaluation, we can firstly see in the row of France in Table 3 that all cross-efficiencies equal 1, which means that France is rated with the maximum efficiency with the patterns of game that all the efficient teams used in their assessments. In other words, the cross-efficiency evaluation identifies France as an "all-round" performer, because it is rated as efficient with a wide variety of models of game. As a result, it ranks 1st: its cross-efficiency score 1 is the largest in the last column of this table. Denmark and Spain are also rated as efficient with the weights of some other teams. France, Spain, Croatia and Slovakia assess Denmark as efficient (aside from Denmark itself), while Spain is evaluated as efficient by Hungary, Korea and Slovakia (apart from by Spain itself). However, other countries give these two teams some poor assessments: Korea and Iceland give Denmark the

scores 1.34 and 1.20, respectively, perhaps due to fact that they both use a very specialized pattern of game, while Norway and Denmark make a similar evaluation of Spain. In the case of Norway, the reason behind the low score (1.38) can also be the specialization of the Norway's game model above mentioned, but in that of Denmark it seems that this team is penalizing Spain (1.21) in forcing it to put more weight on G9m and G6m, which are weaker points of Spain's game. Finally, we can see that all of the teams give good ratings to Slovakia, and this is why it eventually ranks 2nd, together with Denmark and Spain.

The cross-efficiency evaluation has made it possible to discriminate between the teams initially rated as efficient in the DEA self-evaluation. Note that the cross-efficiency score of the teams in the first five positions of the ranking (Croatia is the country ranking 5th) are substantially larger than those of the other four, which are the efficient teams that have used the most unbalanced patterns of game in their assessment (Norway, Iceland, Korea and Hungary). Perhaps as a result, some inefficient teams like Poland and Brazil rank before these four efficient teams.

The comparison between the ranking concerning game performance provided by the cross-efficiency evaluation and the final classification of the championship allows us to conclude that France, which is the world champion, is an "all-round" performer, now in the sense that it is the best regarding both game performance and competitive performance. Denmark and Spain, which were 2nd and 3rd in the tournament, respectively, keep their positions in our analysis, so they are also good performers. However, we can also see differences between both rankings. Among them, we highlight the cases of Slovakia and Brazil on one hand and that of Sweden on the other. While in the ranking provided by the cross-efficiency evaluation Slovakia and Brazil gain 15th and 14th positions, respectively, with respect to the final classification in the world championship, Sweden would lose 13th. Thus, we can conclude that Brazil and Slovakia did not exploit sufficiently in competition the good performance of their game, whereas Sweden showed itself as a strong competitor. It should be noted that Brazil and

Slovakia had poor results in the first round of the championship, when they had to play against teams with more potential. In contrast, we would like to stress the fact that Sweden hosted the Championship, so the emotional factor or the home advantage may have given them some edge, and this might explain their good results in competition when those concerned with the performance of the game are not particularly good.

Conclusions

This paper illustrates the use of DEA and cross-efficiency evaluation for the assessment of game performance of sports teams. In particular,

this study could be useful for coaches of handball teams to improve individual and collective tactics in competition. There are other issues that can also be addressed with these methodologies. For example, although we leave out of consideration such issues like team budgets, etc., the DEA models can incorporate that type of inputs in their formulations, if available, and develop measures of team efficiency. This could also be considered in assessments of performance at the level of players. Likewise, these assessments can be made from a different perspective like that concerned with organizational performance. In general, the results obtained have shown that DEA and cross-efficiency evaluation are useful support tools for coaching and managing sports teams.

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A Kinematics Analysis Of Three Best 100 M Performances Ever

by

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The purpose of this investigation was to compare and determine the relevance of the morphological characteristics and variability of running speed parameters (stride length and stride frequency) between Usain Bolt's three best 100 m performances. Based on this, an attempt was made to define which factors determine the performance of Usain Bolt's sprint and, therefore, distinguish him from other sprinters. We analyzed the previous world record of 9.69 s set in the 2008 Beijing Olympics, the current record of 9.58 s set in the 2009 Berlin World Championships in Athletics and the Olympic record of 9.63 s set in 2012 London Olympics Games by Usain Bolt. The application of VirtualDub Programme allowed the acquisition of basic kinematical variables such as step length and step frequency parameters of 100 m sprint from video footage provided by NBC TV station, BBC TV station. This data was compared with other data available on the web and data published by the Scientific Research Project Office responsible on behalf of IAAF and the German Athletics Association (DVL). The main hypothesis was that the step length is the main factor that determines running speed in the 10 and 20 m sections of the entire 100 m distance. Bolt's anthropometric advantage (body height, leg length and liner body) is not questionable and it is one of the factors that makes him faster than the rest of the finalists from each three competitions. Additionally, Bolt's 20 cm longer stride shows benefit in the latter part of the race. Despite these factors, he is probably able to strike the ground more forcefully than rest of sprinters, relative to their body mass, therefore, he might maximize his time on the ground and to exert the same force over this period of time. This ability, combined with longer stride allows him to create very high running speed - over 12 m/s (12.05 -12.34 m/s) in some 10 m sections of his three 100 m performances. These assumption confirmed the application of Ballerreich's formula for speed development. In most 10 m sections of the 100 m sprint, the step length was the parameter that significantly determined the increase of maximal running speed, therefore, distinguishing Bolt from the other finalists.

Key words: sprinting, world record, kinematic analysis, anthropometric characteristics

Introduction

In the last four years Usain Bolt improved the world record in the 100 m sprint three times, from 9.74 s to 9.58 s. Over the last 40 years this record has been revised up to thirteen times from 9.95 s to 9.58 s. The improvement equals 0.37 s (from 1968 to 2009) which is an increase in performance of 3.72%. By comparison, during the same time period, the 200 m world record was revised six times from 19.83 s to 19.19 s what amounts to 3.33 %.

Sprinting speed is defined with the frequency and the length of strides (Mann and Herman, 1985; Ae et al., 1992; Delecluse et al., 1998; Brüggemann et al., 1999; Gajer et al., 1999; Ferro et al., 2001). These parameters are mutually dependant with their optimal ratio enabling maximal sprinting speed. The increase of speed can be achieved by increased length or frequency of strides. The increase of both parameters simultaneously is quite difficult due to mutual dependency. Therefore an increase in one factor will result in an improvement in sprint velocity,

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as long as the other factor does not undergo a proportionately similar or larger decrease (Hunter et al., 2004). Increased frequency results in shorter stride length and vice versa. Therefore the increase in stride length must be directly proportional with the decrease of stride frequency, especially at the beginning of the race – the initial acceleration phase (Mackala, 2007). This relationship is individually conditioned with the processes of neuro-muscular regulation of movement, morphological characteristics, motor abilities and energy substrates (Mann and Sprague, 1980; Mero et al., 1992; Harland and Steele, 1997; Novacheck, 1998; Coh et al., 2001; Prampero et al., 2005).

According to Hunter et al. (2004) and Bezodias et al. (2008), research investigating the relative importance of developing a long stride length or a high stride rate has been inconsistent across published data. Mann and Herman (1985), Ae et al. (1992) and Bezodias et al. (2008) suggested that SF was a more important contributor to the velocity increase in sprint performance, where Mero and Komi (1985), Gajer et al. (1999), Shen (2000) and Mackala (2007) stated that SL was a more significant variable. However, it is not clear how those two kinematic parameters interact with each other across the entire distance of 100 m in order to accurately identify different phases of the sprint race. No data exist on how world class sprinters manipulate stride frequency and stride length in order to reach optimal efficiency of the sprint run.

The purpose of this investigation was to compare and determine the relevance of the morphological characteristics and variability of running speed parameters (stride length and stride frequency) between Usain Bolt's three best 100 m performances. Based on this, an attempt was made to define which factors determine the performance of Usain Bolt's sprint and, therefore, distinguish him from other sprinters.

The presented reasoning leads to the following hypotheses: the stride length is the main factor that determines the increase of running speed in particular 10 m sections of the entire 100 m distance. Knowledge of the relative influence of stride length or stride frequency on maximal running speed would be of great value to coaches and provide a basis for developing specifically designed training protocols for

maximum speed development.

Material and Methods

Participants

The participants for this study were: a Jamaican sprinter, Usain Bolt (body height = 196 cm, body mass = 93 kg, age = 26 years), current 100 m world record holder (9.58 s) and other world class male sprinters, finalists of: 2008 Beijing Olympic Games (age = 25.3 ± 2.93 years, body height = 176.0 ± 8.40 cm, body mass = 76.7 ± 6.41 kg, and 100 m performance = 9.96 ± 0.05 s (the best result: 9.98 s)), 2009 Berlin World Championships in Athletics (age = 26.7 ± 4.07 years, body height = 177.3 ± 6.40 cm, body mass = 79.0 ± 8.01 kg, and 100 m performance = 9.91 ± 0.10 s (the best result: 9.71 s)), and 2012 London Olympic Games (age = 27.0 ± 3.26 years, body height = 179.4 ± 8.10 cm, body mass = 80.4 ± 8.27 kg, and 100 m performance = 9.86 ± 0.10 s (the best result: 9.75 s)). They were assigned to 2 groups: Usain Bolt and other finalists (n=7 or n=6).

Anthropometric characteristics

Body mass, body height, body mass index (BMI) and age were collected for each participant from:

- a) www.2008.NBCOlympics.com/track/athletes for 2008 Beijing Olympic Games finalists (n=8),
- b) www.trackandfield.about.com/profiles for 2009 Berlin World Championships in Athletics finalists (n=8), and
- c) www.BBC.uk/sport/olimpics/2012/athletes for 2012 London Olympic Games finalists (n=8).

The measurements take into account the changes in age and body mass, if there were such for the sprinters taking part in all three finals. Based on measurements of body mass the current BMI was established. BMI was calculated as the ratio of body mass to the squared standing stature ($\text{kg}\cdot\text{m}^{-2}$).

Measures and procedures

The data collections were conducted at the 2008 Beijing Olympic Games, 2009 Berlin World Championships in Athletics and 2012 London Olympic Games. The data was obtained from video footage provided by NBC TV stations and BBC TV station and available due to the courtesy of TV on the web. After downloading the video footage from the network in order to see the movie frame by frame, the VirtualDub

Programme was applied. The VirtualDub Programme is a video capture/processing utility for 32-bit and 64-bit Windows platforms (98/ME/NT4/2000/XP/Vista/7), licensed under the GNU General Public License (GPL). Through this program, we developed a file format of individual frames where the frames in the video were counted. This enabled the acquisition of basic kinematic data such as: division of the 100 m distance into 10 m sections, average interval time, the number of strides performed, the average stride length calculations, average stride frequency, as well as calculation of running speed for each 10 or 20 m section, at the end of each 10 or 20 m segment. Our data for each 100 m final was compared with other data posted in the web or available by courtesy of the TV station. In turn, our data for the Olympic Games in Beijing in 2008 was compared with data from *speedendurance.com*. However, this data analyzed only five - 20 m sections. The 100 m final in Berlin in 2009 was compared with data obtained and published by the Scientific Research Project Office responsible on behalf of the IAAF and the German Athletics Association (Berlin 2009) for a research project carried out during the competition. The data regarding 100 m final from 2012 London Olympic Games applies only to Usain Bolt and was published by the Spanish newspaper El Pais. The application of VirtualDub Programme allowed measurement only for a selected sprinter. Accurate measurements from a camera were possible only for those sprinters not visually obscured or interfered by other sprinters (placement of the foot on the track). This problem occurs at the beginning of the race (acceleration phase), and between 60 and 90 m of the sprint. The material was read and later developed from commercial recording (TV – NBC, BBC) not from the biomechanical set-up on the stadium directly during 100 m performance. This may imply the inaccuracies and missing data. However, data was compared with the sources and no significant differences were found.

Statistical analysis

In the analysis descriptive statistics were applied. It included the calculation of mean, SD and V (variation). All data were analyzed using the statistics package for windows Statistical Package for Social Science (v. 11,0, Chicago Il.).

Results

Despite the lack of strong evidence (relationship) between body composition and results in the 100 m sprint, we decided to utilize the information of morphological characteristics of Usain Bolt and compare it with other finalists. This information could not be disregarded especially when analyzing the relationship between running speed, length and frequency of strides and the result in sprinting.

Physically, with body height of 196 cm, Bolt is one of the tallest sprinters in the world. The current second highest sprinter is Ryan Bailey from USA of 193 cm. For comparison, Bolt's height is almost 20 cm, 18.7 cm and 16.6 cm greater than the average height of the other finalists (2012 Beijing Olympic Games, 2009 Berlin World Championships in Athletics and 2012 London Olympic Games). On the other hand, body mass shows even greater differences between Bolt and the other sprinters. Bolt, despite greater height, is also heavier than the other sprinters: **Beijing** 14.8%, Berlin 12.3% and 10.7% in London. The disclosed values directly reflect the level of BMI, although the differences are less pronounced (Table 1).

Table 2 contains the basic parameters of three best Usain Bolt sprint performances, compared with the rest of finalists. Bolt completed all three fastest 100m races in an average of 41.13 strides, starting with smaller steps at the beginning of the sprint and covering an average of 2.45 meters with each one. His opponents took about 43-48 strides (the average was: 45.65 strides in Beijing 2008, 44.91 strides in Berlin 2009 and 44.45 strides in London 2012, which gives the average stride length for each competitions (2.19 cm, 2.23 cm and 2.25 cm respectively)). Of course, the stride length is inextricably linked to its frequency, which is about 0.30 Hz lower in Usain Bolt, than in the remaining finalists. Comparing this with Bolt's times (average of three races – **9.63 s**) with that of his rivals (the average of three races - 9.91 s) gives an opportunity to see how he is able to perfectly manage those two kinematic variables in order to reach 12,34 m/s in some 10 m sections of his 100 m performances

Table 3 contains Usain Bolt's 100 m kinematic data with a breakdown to 10 m sections. This table gives us some real insight into Bolt's races. It showed that most of the times in

each 10 m section from Beijing are similar to those from Berlin and London. The differences are on average of 0.02 seconds. Clear differences can be observed only in the first and last 10 m. Despite the better reaction in comparison to the final in Beijing (a difference of 0.019 s), Bolt's first 10 m in Berlin was slower by 0.04 s (total time of the first 10 m section was 1.89 s) compared to his race in Beijing. The second significant difference is in the last 10 m. It cost him about 0.07 s compared to the time needed for the last 10 m in Berlin. That is an important time difference for 10 m. After

deducting the reaction time (0.019 s) from the first 10 m section (1.85 s) performed in Beijing, we can suppose that Bolt would be able to sprint the first 10 m in 1.83 s, or about 0.06 s faster than he did in the final event in Berlin. Thus, a new world record in the 100 m probably would be 9.52 seconds. In London final from 80 to 100 meters Bolt actually began to slow down. We can see that his time for the last 20 meters is 0.06 seconds slower than his fastest 20 meter split of 1.61 seconds. We also know that he reached his average maximum speed 12.34 s (between 60-80 m).

Table 1

Baseline physical characteristics of Usain Bolt and the rest of finalists of the 100 m sprint

Parameters	Olympic Games Beijing 2008 (1)			World Championships Berlin 2009 (2)			Olympic Games London 2012 (3)		
	Usain Bolt	Other Finalists		Usain Bolt	Other Finalists		Usain Bolt	Other Finalists	
		$\bar{X}$	SD		$\bar{X}$	SD		$\bar{X}$	SD
Age (year)	22	25.3	2.93	23	26.7	4.07	26	27.0	3.26
Body mass (kg)	90	76.7	6.41	90	79.0	8.01	93	80.4	8.27
Body height (m)	196	176	3.64	196	177.3	6.40	196	179.4	8.10
BMI (kg /m ²)	23.4	25.5	2.34	23.4	22.5	2.26	24.2	24.9	1.58

1 data from www.2008.NBColympics.com/track/athletes

2 data from www.trackandfield.about.com/profiles

3 data from www.BBC.uk/sport/olympics/2012/athletes

Table 2

Numerical characteristics of selected kinematic parameters in the 100 m sprint:

a) Usain Bolt,

b) the rest of finalists

Kinematic parameters a) Usain Bolt		Olympic Games Beijing 2008	World Championships Berlin 2009	Olympic Games London 2012	Statistics from three competitions		
					$\bar{X}$	SD	V
Time [s]		9.69	9.58	9.63	9.63	0.06	0.57
Velocity [m/s]		10.32	10.44	10.38	10.38	0.06	0.58
Stride frequency [Hz]		4.24	4.23	4.29	4.25	0.03	0.76
Number of strides	All	41.1	40.92	41.4	41.13	0.25	0.61
	Take –off from LL	20.7	20.1	20.9	20.57	0.42	2.02
	Take –off from RL	20.4	20.8	20.5	20.57	0.21	1.01
Stride length [m]		2.43	2.47	2.41	2.44	0.03	1.25

Kinematic parameters b) the rest of finalists		Olympic Games Beijing 2008 (n=7) (1, 2, 3)			World Championships Berlin 2009 (n=7) (3)			Olympic Games London 2012 (n=6) (1, 4, 5)		
		$\bar{X}$	SD	V	$\bar{X}$	SD	V	$\bar{X}$	SD	V
Time [s]		9.96	0.05	0.51	9.91	0.10	1.06	9.86	0.10	0.93
Velocity [m/s]		10.04	0.05	0.51	10.09	0.11	1.01	10.15	0.09	0.92
Stride frequency [Hz]		4.55	0.21	4.68	4.53	0.20	4.41	4.38	0.19	4.44
Number of strides	All	45.69	2.17	4.75	44.91	1.77	3.94	44.45	1.99	4.48
	Take –off from LL	-	-	-	-	-	-	-	-	-
	Take –off from RL	-	-	-	-	-	-	-	-	-
Stride length [m]		2.19	0.11	4.84	2.23	0.09	3.93	2.25	0.10	4.50

1 data from Waren Doscher; 2 data from adrian.sport.com ; 3 data from IAAF –Berlin 2009

4 data from speedendurance.com; 5 hypothetical assumption based on IAAF data

Table 3*Selected kinematic parameters (time and velocity) of Usain Bolt in the 100 m sprint:*

- a) Beijing 2008,
b) Berlin 2009 and
c) London 2012

a) Olympic Games Beijing 2008												
Distance [m]	Mean time [s]*	mean time [s]**	Total time	Mean velocity [m/s]	Total velocity [m/s]	Number of strides	Each 20 m	Total	Stride length [m]	Each 20 m	Stride frequency [Hz]	Each 20 m
0-10	1.85	1.89	1.85	5.40	5.40	7.0	11.1	11.0	1.41	1.82	3.84	3.83
10-20	1.02	0.99	2.87	9.80	6.97	4.1			2.44		4.01	
20-30	0.91	0.90	3.78	10.99	7.94	4.0	8.0	19.0	2.50	2.50	4.39	4.49
30-40	0.87	0.86	4.65	11.49	8.60	3.9			2.56		4.48	
40-50	0.85	0.83	5.50	11.76	9.09	3.9	7.6	26.6	2.56	2.63	4.59	4.55
50-60	0.82	0.82	6.32	12.19	9.49	3.7			2.70		4.51	
60-70	0.82	0.81	7.14	12.19	9.80	3.8	7.4	34.0	2.63	2.70	4.63	4.51
70-80	0.82	0.82	7.96	12.19	10.05	3.6			2.77		4.39	
80-90	0.83	0.83	8.79	12.05	10.24	3.5	7.1	41.1	2.86	2.83	4.22	4.10
90-100	0.90	0.83	9.69	11.11	10.31	3.6			2.77		4.00	

* Data from SportEndurance.com
** Data from VirtualDub

b) World Championship - Berlin 2009												
Distance [m]	Mean time [s]*	Mean time [s]**	Total time	Mean velocity [m/s]	Total velocity [m/s]	Number of strides	20 m Section	Total	Stride length [m]	Each 20 m	Stride frequency [Hz]	Each 20 m
0-10	1.89	1.90	1.90	5.26	5.26	7	11.2	11.2	1.43	1.78	3.68	3.89
10-20	0.99	0.98	2.88	10.20	6.94	4.2			2.38		4.28	
20-30	0.90	0.92	3.80	10.87	7.90	4.0	7.9	19.1	2.50	2.52	4.35	4.54
30-40	0.86	0.83	4.63	12.05	8.64	3.9			2.56		4.70	
40-50	0.83	0.84	5.46	11.90	9.16	3.8	7.5	26.6	2.63	2.67	4.64	4.49
50-60	0.82	0.82	6.29	12.19	9.53	3.8			2.63		4.63	
60-70	0.81	0.82	7.11	12.19	9.84	3.7	7.2	33.8	2.70	2.77	4.51	4.49
70-80	0.82	0.81	7.92	12.34	10.10	3.5			2.86		4.32	
80-90	0.83	0.83	8.75	12.05	10.28	3.4	7.0	40.8	2.94	2.85	4.10	4.23
90-100	0.83	0.83	9.58	12.05	10.44	3.6			2.77		4.34	

*IAAF official data
** Data from VirtualDub

c) Olympic Games - London 2012												
Distance [m]	Average time [s]*	Total time [s]	Total time [s]**	Average velocity [m/s]	Total velocity [m/s]	Number of strides	20 m Section	Total	Stride length [m]	Each 20 m	Stride frequency [Hz]	Each 20 m
0-10	1.91	1.91		5.23	5.23	7.3	11.5	11.5	1.37	1.74	3.82	3.94
10-20	1.01	2.92	2.93	9.90	6.84	4.2			2.38		4.16	
20-30	0.92	3.84		10.87	7.81	4.1	8.0	19.5	2.44	2.50	4.45	4.49
30-40	0.86	4.70	4.69	11.63	8.51	3.9			2.56		4.54	
40-50	0.84	5.54		11.90	9.02	4.0	7.8	27.3	2.50	2.56	4.76	4.70
50-60	0.82	6.36	6.35	12.19	9.43	3.8			2.63		4.63	
60-70	0.81	7.17		12.34	9.76	3.6	7.0	34.3	2.78	2.86	4.44	4.32
70-80	0.81	7.98	7.96	12.34	10.02	3.4			2.94		4.20	
80-90	0.82	8.80		12.19	10.23	3.6	7.1	41.4	2.78	2.82	4.38	4.30
90-100	0.83	9.63	9.63	12.05	10.38	3.5			2.86		4.21	

* Data from VirtualDub
** Data from El Pais

Table 4
Comparison of the 20 m sections time interval, speed, stride length, stride frequency and stride numbers between Usain Bolt and the rest of athletes of the 100 m final of World Championship – Berlin 2009

Usain Bolt - World Championship - Berlin 2009						The Rest of Finalists - World Championship - Berlin 2009									
Distance (m)	Total Time (s)	Mean velocity [m/s]	Mean stride numbers	Mean stride length (m)	Mean stride frequency (Hz)	Total time (s)		Mean velocity [m/s]		Mean stride numbers		Mean stride length (m)		Mean stride frequency (Hz)	
						$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD	$\bar{X}$	SD
0-20	2.88	6.94	11.2	1.78	3.89	2.93	0.02	6.83	0.05	12.09	0.51	1.66	0.07	4.13	0.18
20-40	1.75	11.42	7.9	2.52	4.54	1.81	0.01	11.06	0.09	8.73	0.37	2.29	0.10	4.84	0.23
40-60	1.66	12.05	7.5	2.67	4.49	1.73	0.02	11.54	0.17	8.21	0.31	2.44	0.09	4.75	0.20
60-80	1.63	12.26	7.2	2.77	4.49	1.70	0.03	11.80	0.23	8.06	0.27	2.48	0.08	4.77	0.20
80-100	1.66	12.05	7.0	2.85	4.23	1.75	0.03	11.43	0.20	7.81	0.45	2.56	0.14	4.49	0.30

Figure 1

Individual characteristics of groups of selected kinematic parameters from the 100 m final of 2009 Berlin World Championships in Athletics

Table 5*Differences in interval speed, stride length, stride frequency of Usain Bolt (World Record) in:**a) Olympic Games in Beijing 2008,**b) World Championships in Berlin 2009 and**c) Olympic Games in London 2012*

Descriptive statistic	a) Olympic Games Beijing 2008									
	10	20	30	40	50	60	70	80	90	100
Absolute change in speed (m/s)	5.40	(+) 4.40	(+) 1.19	(+) 0.50	(+) 0.27	(+) 0.43	(+) 0.00	(+) 0.00	(-) 0.14	(-) 0.94
Relative change in speed (%)	0.0	81.5	12.1	4.5	2.3	3.6	0.0	0.0	1.2	7.8
Absolute change in stride length (m)	1.41	(+) 1.03	(+) 0.06	(+) 0.06	(+) 0.00	(+) 0.14	(-) 0.07	(+) 0.14	(+) 0.09	(-) 0.09
Relative change in stride length (%)	0.0	73.0	2.45	2.40	0.0	5.5	2.6	5.3	3.2	3.2
Absolute change in stride frequency (Hz)	3.84	(+) 0.17	(+) 0.38	(+) 0.09	(+) 0.11	(-) 0.08	(+) 0.12	(-) 0.24	(-) 0.17	(-) 0.22
Relative change in stride frequency (%)	0.0	4.4	9.5	2.0	2.4	1.7	2.7	5.2	3.9	5.2

(+) increase, (-) decrease, * Data from VirtualDub

Descriptive statistic	b) World Championship - Berlin 2009									
	10	20	30	40	50	60	70	80	90	100
Absolute change in speed (m/s)	5.26	(+) 4.94	(+) 0.57	(+) 1.18	(-) 0.15	(+) 0.29	(+) 0.00	(+) 0.15	(-) 0.29	(+) 0.00
Relative change in speed (%)	0.0	93.9	6.5	10.8	1.3	2.4	0.0	1.2	2.4	0.0
Absolute change in stride length (m)	1.43	(+) 0.95	(+) 0.12	(+) 0.06	(+) 0.13	(+) 0.00	(+) 0.07	(+) 0.16	(+) 0.08	(-) 0.17
Relative change in stride length (%)	0.0	66.4	5.0	2.4	2.7	0.0	2.6	5.9	2.8	5.8
Absolute change in stride frequency (Hz)	3.68	(+) 0.60	(+) 0.07	(+) 0.35	(-) 0.06	(+) 0.01	(-) 0.12	(-) 0.19	(-) 0.22	(+) 0.24
Relative change in stride frequency (%)	0.0	16.3	1.6	8.0	1.3	0.01	3.6	4.2	5.1	5.8

(+) increase, (-) decrease, * Data from VirtualDub

Descriptive statistic	c) Olympic Games - London 2012									
	10	20	30	40	50	60	70	80	90	100
Absolute change in speed (m/s)	5.23	(+) 4.67	(+) 0.97	(+) 0.76	(+) 0.27	(+) 0.29	(+) 0.15	(=) 0.00	(-) 0.15	(-) 0.14
Relative change in speed (%)	0.0	89.3	9.8	6.9	2.3	2.4	1.2	0.0	1.2	1.2
Absolute change in stride length (m)	1.37	(+) 1.01	(+) 0.06	(+) 0.12	(-) 0.06	(+) 0.13	(+) 0.15	(+) 0.16	(-) 0.16	(+) 0.08
Relative change in stride length (%)	0.0	73.7	5.7	4.9	2.4	5.2	5.7	5.7	5.5	2.9
Absolute change in stride frequency (Hz)	3.82	(+) 0.34	(+) 0.29	(+) 0.09	(+) 0.22	(-) 0.13	(-) 0.19	(-) 0.24	(+) 0.18	(-) 0.17
Relative change in stride frequency (%)	0.0	8.9	7.0	2.0	4.8	2.7	4.1	5.4	4.3	4.9

(+) increase, (-) decrease, * Data from VirtualDub

To better illustrate the differences between Usain Bolt and other world-class sprinters, Table 4 and Figure 1 compared the kinematic fundamental values of the 100 m final in 2009 from Berlin divided into 20 m sections. The individual characteristics of selected kinematic parameters in 100 sprint showed significant differences between sprinters.

Table 5 contains the basic criterion for determining the effectiveness of the speed curve of 100 m sprint. The changes of speed value depend on mutual relations between the stride length and stride frequency. It is evident that up to 40 m at the same time the running speed increases, due to a linear increase in both the stride length and stride frequency. In the later part of the distance, there is a further increase in velocity, although the length and frequency demonstrated a large variable.

Discussion

The purpose of this investigation was to compare and determine the relevance of the morphological characteristics and variability of running speed parameters (stride length and stride frequency) between Usain Bolt's three best 100 m performances. Based on this, an attempt was made to define which factors determine the performance of Usain Bolt's sprint and, therefore, distinguish him from other sprinters.

The influence of Usain Bolt's biological attributes (body height and body mass) on the stride length and stride frequency would be a simplified explanation for his superiority and elements that significantly distinguish him from rest of the finalists. With regard to the body build, type of muscles (dominated by fast-twitch muscle fibers) and training program, there must be some variables which distinguish Bolt from the rest of current world sprinters. Taking into consideration that in sprinting, there are numerous limiting factors such as gravity, ground contact time, muscle build, power that generates the speed of muscle contractions, it may be assumed that some of these variables make him a super athlete, much faster than other sprinters.

Therefore, it is worth noting that Bolt's body height and long lower extremities may be also perceived as a disadvantage taking into consideration the fact that he is much slower than his shorter opponents at the acceleration phase.

On the other hand, longer lower limbs enable Bolt to propel him in the phase with maximum speed (50-80 m) and allow him to maintain his speed till the end of the race. Bolt's body height resulting in long strides makes it possible for him to maintain high speed for a longer time and decelerate at a slower rate than shorter sprinters.

On the contrary, fast sprinters are able to achieve higher running speed by striking the ground with greater force and much quicker than slower sprinters do. This is probably another mechanical element that distinguishes Usain Bolt from other world class sprinters. How hard and how quickly do elite sprinters strike the ground? Back to Weyand et al. (2000), at top speed, every sprinter takes around a third of a second to pick their foot up and put it down again. As we know sprinting speed is largely determined by how much force a sprinter can apply to the ground. Generally, they have two possibilities to sprint faster: strike the ground during the contact phase harder or exert the same force over a longer period of time. Considering these two options, we can partly explain why Bolt is superior compared to other sprinters. He is probably able to strike the ground more forcefully than the rest of sprinters, relative to their body mass, therefore, he might maximize his time on the ground. If we consider the option to exert the same force over a longer period of time, it can generate more power so it increases stride length. His forefoot lands probably a little bit further in front of the knee than in other sprinters, although, it does place tremendous stress on the hamstrings muscles. Bolt has an efficient force generation through stride thrust, greater hip flexibility and is able to sprint faster than other sprinters who had faster stride rates. He is biomechanically superior in leg/hip movement than other sprinters. Despite his body height, he is able to manage body strength during the start and initial acceleration phase to create greater force against the ground. It is necessary to understand that visually this type of sprinting technique is common for most top class sprinters. The differences are very small, almost invisible, what creates the impression that Usain Bolt is not only faster, but also he applies a more efficient technique. However, the lack of details with regard to kinetic data concerning these assumptions does not preclude scientifically reasonable considerations that Usain Bolt

distinguishes himself from other world class sprinters.

Running velocity is the product of stride length and stride frequency ($v = l \times f$) (Luhtanen and Komi, 1978; Mero and Komi, 1985). According to Ballreich (1976), an increase in average velocity (v) and, therefore, a decrease in running time (t) for a given distance, can only result from changes of these two parameters: an increase of stride length (with a decrease of number of strides and their frequency) or inversely, a decrease of stride length (with an increase in stride frequency) (Mackala, 2007). In turn, Delecluse et al. (1998) found a linear relationship between the length of the stride and speed. However their research did not find a significant correlation between stride frequency and speed. On the basis of the Ballreich's (1976) assumption, improving performance in the sprint events depends on five logical possibilities:

1. $V + \Delta V = (L + \Delta L) \times f$ where ($f \sim \text{constant}$)
2. $V + \Delta V = L \times (f + \Delta f)$ where ($L \sim \text{constant}$)
3. $V + \Delta V = (L + \Delta L) \times (f + \Delta f)$
4. $V + \Delta V = (L + \Delta L) \times (f - \Delta f)$; [$(L + \Delta L) \times (f - \Delta f) > L \times f$]
5. $V + \Delta V = (L - \Delta L) \times (f + \Delta f)$; [$(L - \Delta L) \times (f + \Delta f) > L \times f$]

Analyzing Table 6, it can be concluded that running speed increased in 21 of 30 analyzed 10 m sections, which represents 70% of their total number. The decline rate was observed in 5 sections (16%), and remaining 4 sections showed constant velocity (13.3%). In half segments (46.7% of all cases), running speed increased (10, 20, 30, 40, 60, 70 m) due to the increase of both kinematic parameters of the sprint $V + \Delta V = (L + \Delta L) \times (f + \Delta f)$. With these 7 cases, the length of the stride

dominated over the increase of stride frequency, while in 1 case it was the opposite. In 4 cases where the speed was constant compared to previous section, stride length increased three times and stride frequency only once. The decline rate was observed in 5 sections, except for the fact that in three sections, an increase in the length of steps may be noted $V - \Delta V = (L + \Delta L) \times (f - \Delta f)$ and in remaining two sections, an increase occurred in stride frequency $V - \Delta V = (L - \Delta L) \times (f + \Delta f)$.

Similar results were presented in early Mackala's study (2007), which compared the finalists from WC in Tokyo (1991) with the average sprinters. In the final conclusion, the length of stride was a decisive factor with regard to the increase of running speed in each 10 m section. Gajer et al. (1999), who analyzed French best sprinters found that SL was a more important factor contributing to the increase in velocity in sprint performance. Opposite to this statement, Bezodis et al. (2008) conducted a longitudinal case study of stride characteristics in a world class sprinter where the changes in speed occurred as a consequence of changes in stride frequency. This confirms findings of Hunter (2004), who created a map of positive and negative interactions between stride length and stride frequency. He referred to the negative effect that an increase in step length might have on the step rate, and vice versa, as a "negative interaction". Some authors suggest that stride frequency (Mero et al., 1981; Mero et al., 1992), and related aspects (van Schenau et al., 1994; Wood, 1987) are the speed limiting factors in sprint running; whereas others (Armstrong et al., 1981; Summers, 1997; Shen, 2000; Hunter et al., 2004) indicate that a long stride is more important.

Table 6.
*Comparison of the velocity curve for selected phases
of the 100 m sprint due to individual changes of the stride rate and stride length*

Phase	Distance (m)	Olympic Games Beijing 2008	World Championship Berlin 2009	Olympic Games Berlin 2012
1	0-10	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$
2	10-20	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$
3	20-30	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$
4	30-40	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$
5	40-50	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V - \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V + \Delta V = (L - \Delta L) \times (f + \Delta f)$
6	50-60	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$
7	60-70	$V = \text{const} = (L - \Delta L) \times (f + \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$
8	70-80	$V = \text{const} = (L + \Delta L) \times (f - \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V = \text{const} = (L + \Delta L) \times (f - \Delta f)$
9	80-90	$V - \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V + \Delta V = (L + \Delta L) \times (f - \Delta f)$	$V - \Delta V = (L - \Delta L) \times (f + \Delta f)$
10	90-100	$V - \Delta V = (L - \Delta L) \times (f - \Delta f)$	$V = \text{const} (L - \Delta L) \times (f + \Delta f)$	$V - \Delta V = (L + \Delta L) \times (f - \Delta f)$

In the present study, the finding confirming the prevalence of stride length over stride frequency was in line with other studies, nevertheless, it should be highlighted that there is a necessity to develop both, a greater stride rate and stride length (Kunz and Kaufman, 1981; Man et al., 1984; Delecluse et al., 1998). The explanation of this phenomenon was discussed by Hunter et al. (2004) who stated that a longer SL is achieved through long term development of strength and power, while SF may be the key factor in developing greater velocity.

According to the authors of this paper, the possibility of a negative or positive interaction between the two discussed kinematic parameters i.e., stride length and stride rate, is rather limited, even though such a statement may be in contradiction with other studies' results. Furthermore, when considering this issue, it is important to know how an improvement of one factor (i.e., stride length or stride rate) may affect another (Hunter et al., 2000). The main aim consists of reaching an optimal value of both parameters in order to maintain maximal running speed through the entire distance of 100 m. Some results from Table 6 indicate that the sprinter reached optimum relationship (interaction) between stride length and stride frequency. Both variables showed no change in the values;

$V_{const} = (L + \Delta L) \cdot (f - \Delta f)$. This observation should be considered when training an athlete in sprinting.

Conclusions

Bolt's anthropometric advantage (body height and lower limbs length) is not questionable and it is one of the factors that makes him faster than the rest of the finalists of each of the three discussed sprinting events. Additionally, Bolt's almost 20 cm longer stride presents an important benefit in the latter part of the race. Despite these factors, he is probably able to strike the ground more forcefully than other sprinters, relatively to their body mass and, therefore, he might maximize the time of the contact with the ground and apply the same force over this period of time. This ability, combined with longer stride, allows him to reach very high running speed - over 12 m/s (12.05 -12.34 m/s) in some 10 m sections of his three 100 m performances.

Analysis of the obtained results of this particular sprinter may be of great importance for trainers and coaches as it implies work on stride frequency (SF) in order to reach a higher value of maximal sprinting speed. Therefore, it is noteworthy that the main focus should be on the optimal interaction between stride length and stride frequency.

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