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Leg stiffness and potential energy in the countermovement phase and the CMJ jump height

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Summary

Study aim: The elastic potential energy accumulated in the musculotendinous units during the countermovement phase of a jump adds up to the energy supplied by the contracting muscles used in the take-off phase. Consequently, the total mechanical energy used during the jump may reach higher values. Stiffness represents a quantitative measure of a body's elastic properties. Therefore, the aim of this study was to establish the relationship between leg stiffness and the countermovement jump height.
Material and methods: 24 basketball players from the II Division participated in the study. The measurements employed a Kistler force plate and a BTS SMART system for the motion analysis. Each study participant performed three countermovement jumps with arm swings. Leg stiffness in the countermovement phase was determined from the slope of the ground reaction forces curve, with respect to the coexisting height of the greater trochanter of the femur. The decline in the gravitational potential energy of the centre of mass during the countermovement phase is partially accumulated in the form of potential elastic energy through the stretched musculotendinous units, and consequently contributes to the jump height.
Results: We found a statistically significant relationship between leg stiffness and a decline in the potential energy during the countermovement phase. The relationship between leg stiffness and the jump height was not statistically significant.
Conclusions: The distribution of measurements may suggest the presence of local maximums, with their locations representing a value of leg stiffness that allows for high values of changes in the potential energy and the jump height to be obtained. Therefore, the presence of a specific value for leg stiffness that would be the most favourable for the accumulation of potential elastic energy is likely. However, this study cannot unequivocally confirm this fact, and the confirmation of the above statement will require further experimentation.

Key words: Elastic energy – Elasticity – Quasi-stiffness – Stretch-shortening cycle

Introduction

A vertical jump performed with a countermovement (CMJ – countermovement jump) is an example of a type of movement that is based on the stretch-shortening cycle (SCC). The countermovement before the take-off in a vertical jump causes a rapid stretching of the knee extensors. A change in the gravitational potential energy of the centre of mass during this countermovement phase causes an accumulation of potential elastic energy in the compliant tissues. The potential elastic energy accumulated during the countermovement phase then adds up to the energy that is supplied by the contracting muscles and used in the take-off phase. This helps to increase the total mechanical energy used during the jump, resulting in a greater jump height [2, 4, 10, 17]. This phenomenon is regarded as one of the causes of the usually better height that is recorded for a CMJ when compared to a squat jump (SJ – jump performed without a countermovement) [1, 2, 4].

A countermovement with the lower limbs that is too slow (with a small dynamic) will cause the elastic energy accumulated during the eccentric phase to be partially dissipated, e.g. in the form of heat [2, 4]. The half-life for elastic energy is 0.85 s and its total dissipation occurs after four seconds. Therefore, a time of over one second between the muscle stretch and its contraction will cause the muscle to stop behaving as a spring which, after the stretching force ceases, returns to the previous state and releases all the accumulated energy [19]. In this case, the jump will be performed as if it was started from a fixed static position with an isometric muscle contraction (SJ), which will have a negative effect on the jump height. Therefore, during movement tasks that are aimed at reaching a high final

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velocity of the body movement, changes in the directions of movement during the stretch-shortening cycle should occur in the shortest possible time, while maintaining an optimal range of the countermovement. Each moment of delay reduces the elastic energy contribution to the energy balance in the muscles during the concentric phase of the movement.

Potential elastic energy is the energy determined for a body that is deformed elastically. Therefore, it can be adopted for the deformations occurring in the lower limbs of a person who performs a vertical jump. The potential elastic energy of the elastic body with a linear profile is proportional to the squared strain:

$$E_{ps} = \frac{1}{2} \cdot K \cdot \Delta l^2, \qquad (1)$$

where E_{ps} is potential elasticity energy, K is stiffness and Δl is the change in length. Stiffness (the ratio of the value of the cause of the displacement to the quantitative measurement of the displacement) represents a quantitative measurement of the body's elastic properties. Leg stiffness is a concept that relates to the limb as a whole system, rather than only to the musculotendinous systems. With this approach, the limb's substitute stiffness depends on the stiffness of all the compliant tissues such as the ligaments, blood vessels and bones [9].

Theoretically, the lower limbs, through increased stiffness, are capable of the accumulation of a greater amount of elastic energy, assuming there are relatively constant (unchanged) dimensions of the deformation. Therefore, it can be assumed that a higher value of leg stiffness should positively affect the height of a vertical jump and the overall take-off efficiency. However, the phenomenon of elastic hysteresis might cause a decline in the value of leg stiffness during the take-off phase, when compared to the countermovement phase, as a result of a partial loss of the accumulated elastic energy. Therefore, a question can be asked about the relationship between leg stiffness in the countermovement phase and the vertical jump height, and whether there is a value for leg stiffness at which the amount of accumulated potential elastic energy is the highest? The aim of this study was to establish the relationship between leg stiffness and the countermovement jump height.

Material and methods

The study was conducted among 24 basketball players from the II Division. The study group was characterised by the following mean parameters (±SD): body height – 191.4 ± 7.0 cm; body mass – 82.1 ± 7.5 kg; and age – 19.0 ± 1.6 years. The training experience was 7.4 ± 2.5 years. The experiments were performed in the Biomechanical Analysis Laboratory (with PN-EN ISO 9001:2009 certification). Prior to the tests, the participants were familiarised with the purpose of the study and signed a written consent for their participation in the experiment. The research project was approved by the Senate's Research Bioethics Commission, and the procedures complied with the Declaration of Helsinki regarding human experimentation.

The ground reaction forces were measured using two Kistler force plates (9286A) in order to ensure a separate measurement of the ground reaction forces for each limb. The kinematic data was recorded by the BTS SMART system (BTS Bioengineering, Milan, Italy) for a comprehensive motion analysis based on the technology of passive markers that reflect infrared radiation (IR). The system features 6 cameras with a frame rate of 120 Hz. In order to facilitate a synchronisation of the measurements, the sampling rate for the signal from the force plates was set at 240 Hz [6]. The BTS SMART Analyser software aided in the synchronisation of the recorded data and the preparation of a report from the measurements.

Before the test, all of the study participants underwent an individual warm-up procedure, which consisted of a continuous shuttle run over a distance of 10 m. The run occurred at a moderate pace of ca. 10 lengths of the distance per minute, and was continued until the athlete's heart rate reached 150 bpm. During the body weight measurement, the participants stood on the plates (each foot on a separate plate) and maintained their body in a motionless position for 5 seconds. The reflection markers were located at the height of the greater trochanters of the femur. Therefore, a measurement of the l variable, which was the height of the markers located at the greater trochanters of the femurs (used as a conventional upper end of the lower limbs), was also possible.

Each study participant performed three countermovement jumps with arm swings. First, study participant stood on the plates so that each limb was placed on a separate plate. At a signal, the person performed a vertical jump, preceded by a rapid countermovement of the lower limbs and accompanied by arm swings. The landing was performed on the same plates as the take-off. Further analyses were based on the highest CMJ for each participant. The jumping height was calculated based on the flying phase time.

Leg stiffness in the countermovement phase was evaluated as a ratio of the changes in the ground reaction forces to the respective changes in the height of the greater trochanter of the femur (used as a conventional upper end of the lower limbs). Leg stiffness was calculated for the part of the countermovement phase where the slope of the F curve with respect to the Δl axis was relatively constant and the $F(\Delta l)$ profile was nearly linear. It was only in this range where an expression of the leg stiffness was possible by means of a (single) numerical value. In the countermovement phase, this was the part between the lowest value of the ground reaction force and the lowest location of the greater trochanters of the femurs. Therefore, this calculation was only approximate in the above range of the $F(\Delta l)$ curve slope, with its slope coefficient equal numerically to the stiffness [15, 16].

The decline in gravitational potential energy of the centre of mass during the countermovement phase was partially accumulated in the form of potential elastic energy through the stretched musculotendinous units, and consequently contributed to the jump height [2, 4, 10, 17]. The change in the potential gravitational energy was evaluated using the equation:

$$E_p = m \cdot g \cdot \Delta l, \quad (2)$$

where E_p denotes the lost part of the gravitational potential energy, m is the body mass, g is the acceleration due to gravity and Δl is the change in the height of the greater trochanter of the femur.

The normality of the distributions for each variable was tested using the Shapiro-Wilk and Lilliefors tests. Due to the lack of a normal distribution of the variables, the Spearman's rank correlation coefficient was used for an examination of the relationships between individual variables. The level of significance was set at $\alpha = 0.05$.

Results

The following mean values (±SD) of the variables which describe the highest CMJs for each participant were obtained: jump height – 0.46 ± 0.04 m; leg stiffness in the countermovement phase – 7.4 ± 2.3 kN/m; and decline in potential energy in the countermovement phase – 202 ± 30 J.

We found a statistically significant relationship between the leg stiffness and a decline in the potential energy in the

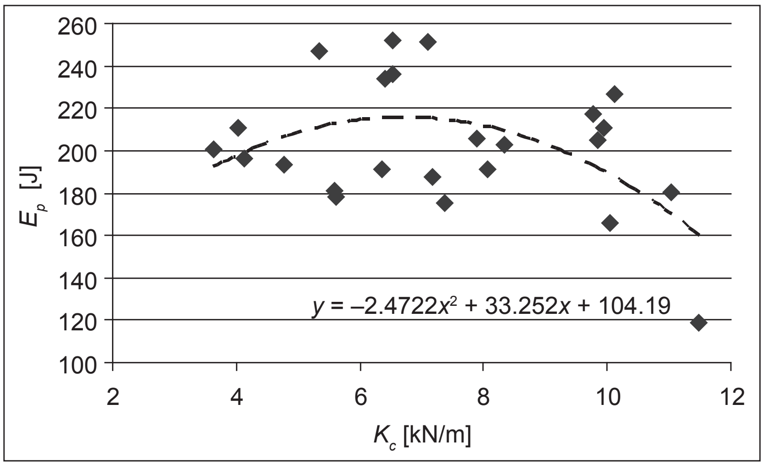

Fig. 1. Decline in potential energy (E_p) versus leg stiffness in the countermovement phase (K_c) with the curve that represents distribution of points by means of second order polynomial

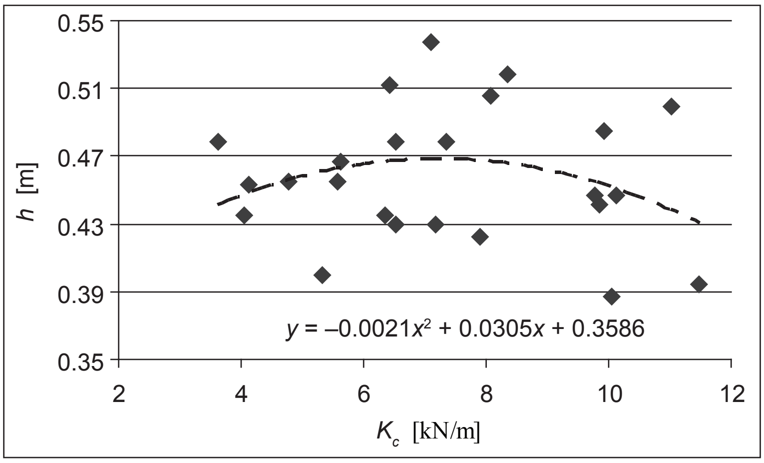

Fig. 2. CMJ height (h) versus leg stiffness in the countermovement phase (K_c) with the curve that represents distribution of points by means of second order polynomial

countermovement phase ($r = -0.45$). However, the relationship between the leg stiffness in the countermovement phase and the jump height was not statistically significant. The above relationships are illustrated in Figures 1 and 2.

The distributions of points in Figures 1 and 2 may suggest that the relationships we have studied are not homogeneously linear. Therefore, the relationship between the variables might have a local maximum, which would represent the value for leg stiffness that would theoretically allow a person to obtain the highest value for the change in potential energy and the jump height. Hypothetically, it is possible to describe the distribution of points using the second order polynomial and to determine the extremum of the function. In the relationship from Figure 1, the extremum was 6.7 kN/m (0.08 kN/m·kg); whereas in Figure 2, this extremum was 7.3 kN/m (0.09 kN/m·kg).

Discussion

The leg stiffness analysed in the present study is not the stiffness viewed in strict terms, due to a substantial contribution of other factors that have an effect on the $F(\Delta l)$ relationships that occur especially during transient states. The stiffness of the components in a human body's motion system does not meet all of the criteria of formal accuracy, and consequently is subject to error. If the measurement of stiffness is not performed in a steady state of body deformation (equilibrium), the substantial value of dF/dl might also contain components that originate from inertia and damping forces [9].

Since leg stiffness represents a quantitative measurement of the elastic properties of the lower limbs, it can be assumed that a higher value for leg stiffness should positively affect the height of a vertical jump and the overall take-off efficiency. This suggestion may be confirmed by the substantially greater values for leg stiffness recording during hopping in athletes, when compared to untrained subjects [13]. Furthermore, Lloyd et al. [11] reported an increase in leg stiffness during hopping following a 4-week plyometric training programme. However, we did not find a significant relationship between leg stiffness in the countermovement phase and the CMJ height. This might suggest a relatively small contribution of potential elastic energy to the vertical jump, or its excessive loss during the countermovement and take-off phases. Anderson and Pandy [2] suggested that the utilisation and storage of elastic energy might enhance jumping efficiency much more than it enhances the overall jumping performance.

Laffaye et al. [7] reported that the increase in a one-legged jump height after a short approach run causes a decrease in leg stiffness. Furthermore, differences in the values of leg stiffness between advanced and beginner athletes, and between advanced representatives of various sports, have also been found. Laffaye and Choukou [8] stated that the minimum value for leg stiffness is the most beneficial for a drop jump (DJ – jump performed immediately after landing from a specific height). Also, Rabita et al. [13] reported a statistically significant (negative) relationship between the leg stiffness and the height of maximal hopping in elite long and triple jumpers. Arampatzis et al. [3] showed the maximum DJ height that can be achieved for various leg stiffness values, which was affected by a reduction in the take-off time. Furthermore, the value for leg stiffness decreased with the increase in the initial drop height that was used (20, 40 or 60 cm). However, all of the above relationships were recorded for types of vertical jumps other than a CMJ. Therefore, the relationships are not necessarily analogous.

Leg stiffness is a variable that is very rarely used for the description of a CMJ [1, 10, 15, 16, 18]. With respect to vertical jumps, the concept of leg stiffness has been used primarily in relation to cyclic jumps, i.e. hopping. Therefore, there is no unequivocal answer to the question concerning the relationship between leg stiffness and the CMJ performance [5, 12, 14, 16]. Struzik and Zawadzki [15] found that a higher value of body mass, body height or the length of the lower limbs was accompanied by a higher value for leg stiffness. However, Wang [18] did not find a statistically significant difference for values of leg stiffness between young and older male adults. Furthermore, Liu et al. [10] reported that leg stiffness, in terms of storing elastic energy and optimising the performance during a CMJ may decrease with age. The authors also demonstrated a statistically significant positive relationship between leg stiffness and the work done by the muscles of the lower extremities during the concentric CMJ phase. In the present study, we found a statistically significant negative relationship between leg stiffness and a decline in the potential energy in the countermovement phase of the CMJ. Therefore, the increase in the value of leg stiffness was accompanied by a decline in the capability to store potential elastic energy by the musculotendinous units during an eccentric activity. Although the above relationship may seem surprising, it should be noted that each jump in the analysis was characterised by a different value for the strain. Therefore, this relationship may directly result from the structure of Equation 1. The above relationship can also explain the lack of a statistically significant relationship between leg stiffness and the CMJ height.

The similar locations of the extrema for the curves presented in Figures 1 and 2 leads to the presumption that there is a specific value for leg stiffness which is the most beneficial for the storage of potential elastic energy, and the most conducive for reaching a maximum CMJ height. This presumption regarding the existence of an appropriate (desirable) leg stiffness that will allow for the maximum performance has previously been made by other authors

[3, 12, 17]. However, this thesis has not been unequivocally supported by the scientific evidence. Arampatzis et al. [3] claimed that an "optimal" level of leg stiffness is needed for the maximisation of the values of mechanical power during a DJ. If the assumption is made that there is a most appropriate level of leg stiffness, the statistically significant negative relationship between leg stiffness and the changes in gravitational potential energy in the countermovement phase found in our study would suggest that there is a rapid decline in the capability for the accumulation of potential elastic energy after it exceeds the most appropriate value for leg stiffness in the countermovement phase. The above assumption would also explain the lack of a statistically significant relationship between leg stiffness and the CMJ height. However, this study cannot unequivocally confirm the presence of an appropriate value for leg stiffness. The statements contained in this paragraph are only presumptions, but may suggest the directions for further research. Therefore, further experiments are needed to support these statements.

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