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Brief communication (Original)

Tibiofemoral joint reaction force during the stance phase of backward- and forward-walking at variable speeds

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Background: The knee is the joint that often suffers from sport injury. Adequate post-injury rehabilitation helps the patients come back to the game earlier, and prevents re-injury. As part of the program, backward-walking is sometimes used, but information available for the knee-joint reaction force is limited.
Objective: Determine tibiofemoral joint reaction force (TFJRF) during the stance phase of backward- and forward-walking at variable speeds.
Methods: Fifty-four healthy Thai males (age 20 to 39 year old, body mass index <30) performed forward- and backward-walking on a split-belt treadmill to record the ground reaction force (GRF) on the force platform under each belt. The subjects were controlled to walk from the slowest to fastest speeds (0.8, 1.0, 1.2, 1.4, and 1.6 m/second). Kinematic data were recorded using six cameras, and analyzed by the motion analysis software. Based on the obtained kinematic and GRF data, TFJRF was calculated using an inverse dynamic model. Heart rates (HR) were also recorded using wireless electrocardiography.
Results: Backward-walking produced higher peak TFJRF during the stance phase than that of forward-walking in every speed. The subjects had higher HR in every speed during backward-walking, but the average TFJRF was lower in all test speeds except 0.8 m/second.
Conclusion: Peak TFJRF and HR during backward-walking were higher than those during forward-walking in every speed, but backward-walking showed a trend to lower the averaged TFJRF compared with forward-walking. In clinical practice, lower speed of backward-walking may be appropriate to prescribe as an exercise for those with tibiofemoral joint problems.

Keywords: Backward walking, inverse dynamics, joint reaction force, split-belt treadmill, stance phase

Knee is one of the joints that suffer from injury by sports and exercises [1]. Adequate post-injury rehabilitation program helps the athletes come-back to the game in a short time, and prevents re-injury. Forward-walking is recommended for rehabilitation, exercise, and training. At the same time, backward-walking is sometimes used as a part of these activities [2].

In general, reaction forces at the knee-joint increase as walking speed increases. For this reason, people with knee problems or previous knee injury may be not able to increase the walking speed to reach their moderate exercise intensity. Therefore, it is of sports medicine application to know knee joint reaction forces during forward- and backward-walking at variable speed.

Flynn and Soutas-Little [3] reported that peak patellofemoral compression force was 46.4% smaller in backward running than that of forward running, and recommended backward running for those with patellofemoral pain syndrome. According to Neptune and Kautz [4], backward stationary pedaling produced 33.1% more peak patellofemoral compression force but 46.5% less peak tibiofemoral compression compared with forces of forward pedaling, and backward pedaling was preferred for those with knee osteoarthritis or meniscus damage but not preferred for those with patellofemoral pain.

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Forward- and backward- direction activity includes walking, running, and pedal-cycling. Currently, the information of reaction force at knee joint is available in forward direction, but is very limited in backward direction. Up to date, no information about reaction force at tibiofemoral joint in backward walking has been presented. In this study, we determined tibiofemoral joint reaction force (TFJRF) of backward and forward walking using a cross-sectional descriptive research design. Subjects walked on the split-belt treadmill for single-leg analysis. An inverse dynamic model was used to calculate TFJRF indirectly.

Materials and methods

Subjects were healthy Thai male volunteers with the age between 20 and 39 years old and without obesity, body mass index (BMI) lower than 30 [5], and signed inform consent. The present study was approved by the Institutional Review Board, Faculty of Medicine, Chulalongkorn Univerisity.

All subjects consumed adequate water and sleep adequately at the night before data collection, and refrained from consuming alcohol, caffeine, or heavy meal for two hours before data collection. In addition, vigorous physical activity and exercise were not allowed 24 hours prior to the test session [6].

At the day of data collection, basic history taking and physical examination were done. The subjects filled the record form, and took off any adornment and wore the vest and skin-tight above-knee shorts. They were measured bear-foot weight and height on weighing device (Tanita, Tokyo, Japan) for BMI calculation (kg/m^2). Resting HR and blood pressure were measured by a researcher via a sphygmomanometer and one-minute pulse palpation.

Two electromyography electrodes (Ambu, Ballerup, Denmark) were placed on subject's anterior chest wall, at right 2nd sternocostal articulation area and left 6th rib in mid-clavicular line to record heart rate (HR) continuously via the wireless electrocardiography (Alive Heart Monitor, Queensland, Australia). Ten reflective markers were applied on the surface anatomy landmarks on both sides of the body. Markers applied at acromian process of scapula, greater trochanter of femur, lateral epicondyle of femur, lateral malleolus, and lateral side of 5th metatarsophalangeal joint.

Instrumental setting-up

Six light-reflex cameras (Proreflex MCU 1000, Gothenburg, Sweden) was set around a split-belt treadmill (TM-06-B) embedded with two force plates (Bertec Corporation, Ohio, USA). All data were input to analyze with the motion analysis software (Qualisys Track Manager, Gothenburg, Sweden). Cameras and force plates were recorded synchronously at 100 Hz.

A digital video (DV) camera (Panasonic, Osaka, Japan), was placed behind the subjects to review for completeness of treadmill-belt contact of each foot. A light bulb in front of the DV was turned on during the second minute of each walking speed to indicate the period for biomechanical analysis. Two emergency stop buttons were hanged on the rails for emergency.

Walking protocol

A subject was required to perform two trials, forward- and backward-walking. Sequence of the walking direction was randomized. The trial began with warm-up to familiarize with walking on split-belt treadmill. Walking speeds started with 0.8 m/second, and stepped up to 1.0, 1.2, 1.4, and 1.6 m/second every minute. The total time of warm-up and familiarization was five to 10 minutes. The subject took a rest until HR was within 10 beats/minute of resting HR. Then, data collection started with speed of 0.8 m/second and stepped up in the same sequence. The duration of each speed was three minutes to stabilize walking pattern and HR. Cool-down period was performed by continuous walking with speed 0.8 m/second for the next two minutes. Then, the subject got off the treadmill and took a rest about 10 minutes. The second trial in the opposite walking direction was conducted in the same sequence.

If the subject stumbled, could not catch up the treadmill-belt speed, or had a risk of falling, he could walk with holding the rails and adjust position. Test could resume when he could walk without holding the rails. Indications for stopping the trial were adapted from general indications for stopping an exercise test in low-risk adults [7].

Data collection and analysis

Ten consecutive gait cycles were chosen to reduce variation among strides. Data from the right side of body were analyzed. In case that DV images confirmed foot slipping outside the treadmill belt, the stride was removed from analysis. Ground reaction force (GRF) was collected and normalized from Newton (N) to percent of body weight (%BW).

Kinematic data were brought to find acceleration of the thigh, shank, and foot segments. Acceleration was calculated from positional data of each segment. Based on the accelerations and GRF, TFJRF during stance phase was calculated using an inverse dynamic model [8]. During both directions of walking, HR was recorded. The averaged HR during 10 seconds before speed adjustment of each level was determined as the HR of those speeds.

Mean±standard deviation (SD) was reported for quantitative data. All analyses were performed on the Statistical Package for the Social Sciences version 10.0 (SPSS, Chicago, USA). A α-level of 0.05 was used to determine statistical significance. Mean of maximum values of TFJRF, and average values of total TFJRF during overall stance phase of all subjects were compared between forward- and backward-walking at each speed by paired student's t-test.

Results

Out of 65 subjects recruited for the study, 11 people were excluded from analysis, because their walking motion was disturbed by non-smoothness perception of treadmill belt rolling. Baseline physical characteristics of the remaining fifty-four subjects were described as mean and standard deviation. The age, body mass, height, and BMI of subjects were 25.2±4.4 years, 61.62±6.23 kg, 170.6±5.0 cm, and 21.2±1.8, respectively. Resting HR and blood pressure were 73.2±10.1 beats/minute, and 125.0±10.7/73.4±9.4 mmHg.

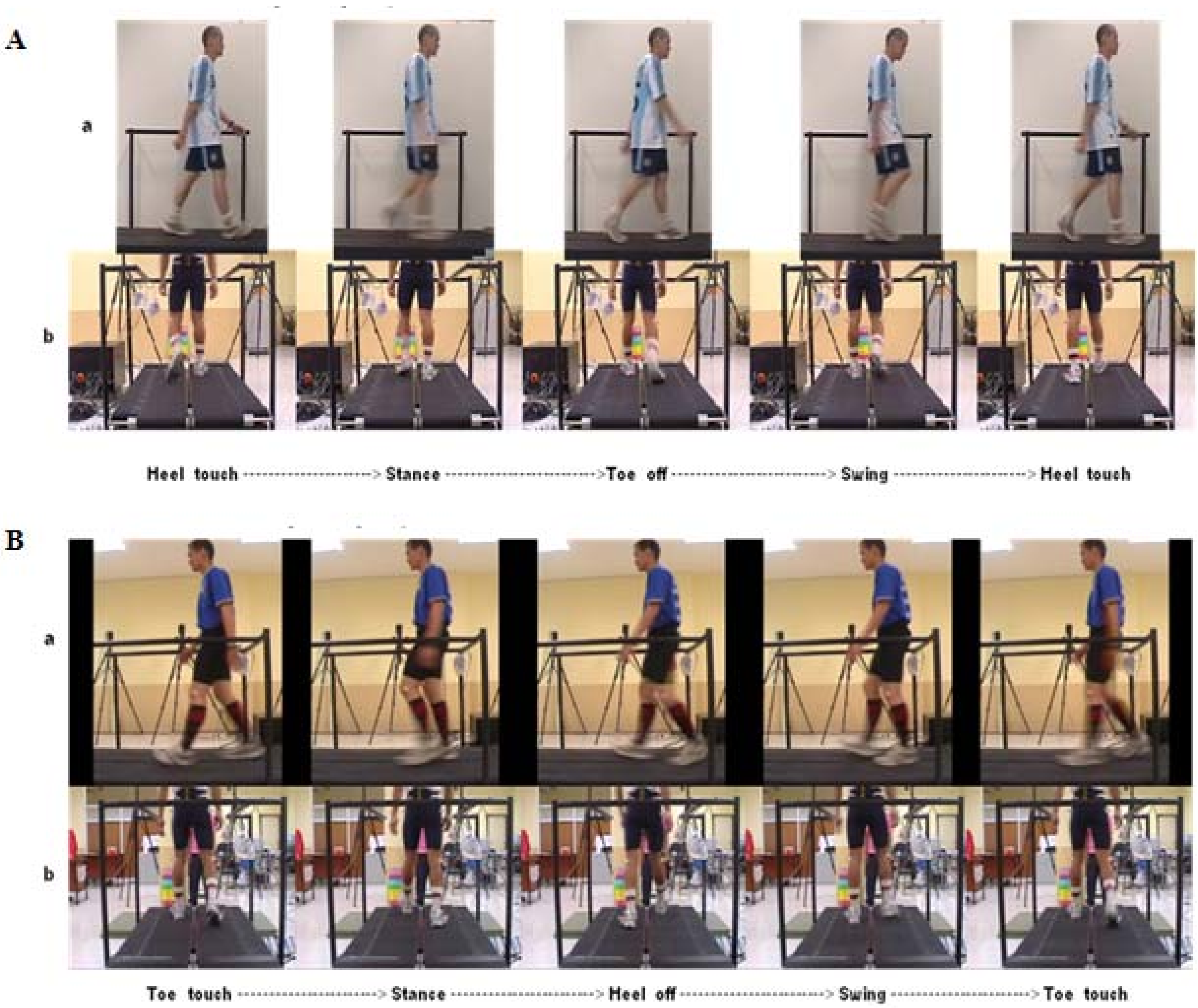

Figure 1. One gait cycle of forward-walking (**A**) and backward-walking (**B**) on the split-belt treadmill. **(a)** lateral view, **(b)** posterior view.

Walking results

Walking data from 54 subjects was further analyzed. All subjects could complete forward-walking. Only thirty-four (63.0%) subjects completed backward-walking. Three (5.6%), seven (13.0%) and ten (18.5%) subjects stopped at the speed of 1.2, 1.4, and 1.6 m/second, respectively. Eighteen subjects stopped backward-walking due to severe fatigue. Two subjects were stopped because their HR reached the predicted maximal HR.

In forward-walking, subject started stance phase with heel touch and terminated with toe off, while in backward-walking, subject started stance phase with toe touch and terminated with heel off. **Figure 1** shows one gait cycle of walking on the split-belt treadmill. Wider base support and more lateralization of foot contact were detected during backward-walking.

Biomechanical data of walking

Both kinematic and kinetic data were not filtered to preserve peak force of ground impact. **Figure 2** shows ground reaction force (GRF) measured over a step of forward- and backward-walking. We note that the pattern in vertical axis was similar for both directions. The breaking peak and propulsive peak was similar in the magnitude during forward-walking, but the breaking peak was clearly higher during backward-walking.

Maximal (peak) and averaged Tibiofemoral joint reaction forces (TFJRF) were separately compared in forward-walking and backward-walking for all speeds. **Table 1** shows mean±SD of TFJRF. We note that the higher the speed of locomotion, peak of TFJRF was higher. Peak TFJRF were statistically significantly higher in backward walking in every speed. Although average TFJRF increased as walking speed increased in forward- and backward-walking, the rate of increment was higher on forward walking. Therefore, average TFJRF of forward walking was higher than that of backward walking significantly as walking speeds was over 1.2 m/second.

Heart rates

For the speed of 0.8, 1.0, 1.2, 1.4, and 1.6 m/second, the averaged HRs of forward-walking were 96.2±14.5, 99.3±15.3, 103.3±14.3, 108.8±14.4, and 113.8±15.1, respectively. The averaged HR's of backward-walking were 109.7±14.5, 120.4±17.6, 134.6±19.1, 149.6±19.3, and 163.2±16.2, respectively. For every speed, HR was higher in backward walking. Interestingly, backward-walking required much more exertion than forward walking especially on high speeds.

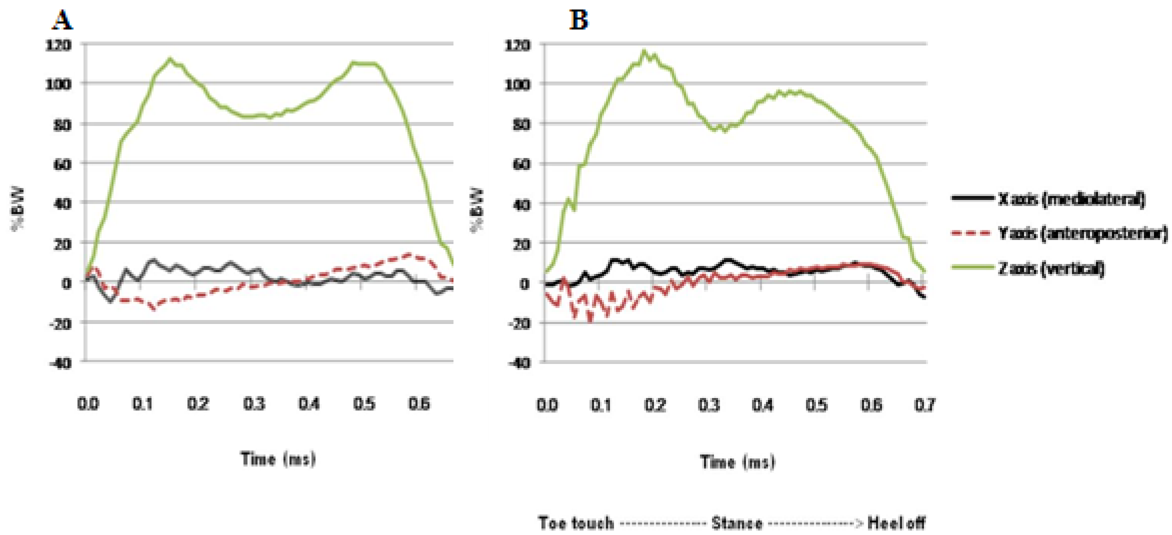

Figure 2. Ground reaction force (GRF) in three axes (at speed 1.0 m/s) over a step of forward-walking (**A**) and backward-walking (**B**) (from a subject). Medial and anterior directions are positive in x- and y-axis, respectively.

Table 1. Tibiofemoral joint reaction forces (TFJRF) (%BW) (mean±SD).

Speed (m/s)	0.8	1.0	1.2	1.4	1.6
A. Maximum (peak)					
Forward	109.42±3.23	112.92±3.01	119.73±3.81	126.27±5.77	136.73±4.63
Backward	125.02±8.55	131.36±10.59	135.48±12.75	141.94±19.08	160.98±20.57
P-value	0.002	0.002	0.004	0.020	0.009
B. Averaged					
Forward	81.36±1.85	83.80±1.59	86.06±1.31	88.65±1.76	90.66±1.56
Backward	82.77±2.43	83.27±2.14	83.53±1.56	83.98±3.10	84.78±3.22
P-value	0.111	0.449	0.002	0.004	0.001

Discussion

Forward-walking is a daily activity, and our subjects could complete forward-walking at all test speeds. The averaged HR of forward-walking at 1.6 m/second was 113.8. At the speed 1.6 m/s, forward-walking could be considered as a light exercise [7]. In fact, the present speed was much lower than forward-preferred transition speed (1.99±0.20 m/second) [9] and forward-metabolic transition speed (2.00-2.19 m/second or 2.16 m/second) [10, 11]. At our highest test speeds, all subjects could perform faster walking without the insight to adapt to run to preserve energy.

Backward-walking is not a regular activity, and our 20 subjects (37%) could not perform high speeds of backward-walking. In fact, some healthy male subjects had difficulties in backward-walking. In our post-test interview, most fatigued muscle groups were knee extensors, calf and ankle dorsiflexors. Our results agreed with the study by Grasso et al. [12] where electromyographic (EMG) activity of most leg muscles was higher in backward-walking than forward-walking at the same speed. As the walking speed increased, the EMG activity of each leg muscle increased curvilinearly, especially in high speeds of backward-walking. Energy requirement of the lower extremity would be a definite factor of the localized fatigue. Whole body energy requirement can also be a factor that caused two subjects to exceed over their maximum predicted HR during backward-walking.

For all walking speeds, HR's were higher in backward direction. Myatt et al. [13] reported that the averaged HR during backward-walking increased exponentially from 99 to and 172 m/second [13]. Flynn et al. [14] found higher HR during backward-walking at 1.8 m/second and running at 2.8 m/second [14]. Our results agreed with their results. Backward-walking with speeds over 1.2 m/second would be defined as moderate exercise intensity (64-76% HR max) [7]. The mean of the maximum HR percentage for this speed was 69.20±10.37. Backward-walking with speed of 1.6 m/second would be at the level of vigorous intensity.

As the walking speed increased, the breaking peak of vertical GRF during forward- and backward-walking increased. Breaking peak of backward-walking was higher than forward-walking (115.0± 17.6 %BW *vs.* 100.8±4.4 %BW) at the same speed [12]. The peak TFJRF also increased as the walking speed increased. Backward-walking had higher TFJRF than forward-walking at every speed.

The average TFJRF were similar in both forward- and backward-walking at slow speeds. These values were lower in backward-walking when walking speeds was over 1.2 m/second. With higher impact peak of backward-walking, the TFJRF of the remaining phase should be lower than that of forward-walking especially at higher speeds. Lower TFJRF was obviously detected especially during the propulsive phase of backward-walking. It is suggested that forward- and backward-walking might pose a risk to tibiofemoral joint in different situations. Higher peak TFJRF of backward-walking tended to result in acute injury, while higher average TFJRF of forward-walking inclined to cause chronic injury. Nevertheless, injury that might be caused form TFJRF still requires further investigation.

It may be possible to train backward-walking for reducing impact peak. Terblance et al. [15] studied the effect of backward-walking and run training on cardiovascular system, muscle metabolism, and body composition, and showed improvement of all the variables. While backward-walking might not be a practical exercise, the training might provide backward-walking an option for exercise especially for people with injury or pain at the tibiofemoral joint due to lower TFJRF at similar exercise intensity level. However, location, light, and environment of training should be concerned to prevent falling and any accident.

This study used an inverse dynamic model to calculate TFJRF, which was an indirect measurement. Biomechanical calculation was up to the selected models and their assumptions. The results might vary among models. Kaufmann et al. [16] used knee-implanted transducer to directly measure tibiofemoral force. However, the operation was invasive and had high risks of complication. Models may be verified by comparing their accuracy with those of direct measurement.

In conclusion, backward-walking produced higher peak TFJRF during the stance phase than forward-walking. It produced lower TFJRF than forward-walking with the same exercise intensity. Therefore, it could be considered as an exercise prescription or rehabilitation program for those with tibiofemoral joint problems.

The authors have no conflict of interest to report.

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