JPFSM: Regular Article

Relationships between lower-limb joint kinetic parameters of sprint running and rebound jump during the support phases

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Received: December 17, 2015 / Accepted: March 3, 2016

Abstract We investigated the relationships between the lower-limb joint kinetic parameters of sprint running and rebound jump during the support phases in 16 male track and field athletes performing sprint running and rebound jump at maximal effort. Sprint running velocity and rebound jump index (i.e., jump height divided by contact time) during rebound jump were calculated. Lower-limb joint kinetic parameters (joint torque and power) during the support phases of these activities were calculated using a force platform and data from a high-speed video camera that recorded movements in the sagittal plane. No significant correlation was observed between sprint velocity and rebound jump index. However, significant correlations were observed between sprint running and rebound jump for mean ankle-joint torque and mean knee-joint torque in the eccentric and concentric phases, as well as for mean negative ankle-joint power and mean negative knee-joint power. These results suggest mechanical similarities in ankle- and knee-joint kinetic parameters, especially in the eccentric phase of sprint running and rebound jump, although such similarities were not observed for sprint velocity and rebound jump index.

Keywords: ankle joint, knee joint, plyometric training, biomechanics

Introduction

Sprint running (sprinting) is critical to performance in many sports. To improve sprint performance, it is necessary to increase the mechanical output of lower-limb muscles during the support phase, as it is the only phase in which the entire body undergoes acceleration and deceleration. Plyometric training using jump exercises can increase mechanical output in sprinting. Many studies have investigated the relationship between sprint performance and the performance of various jumps, including vertical jumps (countermovement jump, drop jump, and rebound jump) and horizontal jumps (bounding). Due to the significant correlation between sprinting and jumping abilities, most types of jumping are important for sprinting, and therefore, these jumps are also useful training exercises for improving sprint performance. However, the relationship between the performance of sprinting and the performance of bounce-type or rebound-type double-leg jumping in the vertical direction (jumping as high as possible with minimum ground contact time, as shown in the rebound jump) remains unclear. The few studies investigating this relationship have shown no correlation, suggesting that the performance of the rebound jump may not be important for sprinting.

The benefits of plyometric training are influenced by the induced joint torque and power of the plyometric exercise. Therefore, in order to develop a suitable plyometric training plan, it is important to understand the relationship between the joint kinetic parameters in sprinting and jumping exercises. The characteristic joint kinetic parameters of rebound jump including the counter-movement jump vs. counter-movement-type drop jump vs. rebound-type drop jump using a double-leg jump in the vertical direction, double-leg vs. single-leg jump in the vertical direction, and vertical vs. horizontal direction have been investigated. Such studies have shown that the rebound jump has the highest ankle-joint kinetic parameters (joint torque, joint power, and joint work) of these jumps. Moreover, rebound jump performance is known to be primarily affected by the ankle joint. During sprinting, the ankle joint plays an important role in achieving high sprinting performance by producing a large vertical force, reducing ground contact time, and enhancing mechanical efficiency. Studies indicate that the ankle joint is also important for rebound jump performance, similar to that observed in sprinting performance. Thus, it seemed likely that there is a relationship between ankle-joint kinetic parameters for sprinting and rebound jump.

The purpose of this study was to investigate the relationship between lower-limb joint kinetic parameters during the support phase of sprinting and rebound jump. We
hypothesized that a relationship existed for ankle-joint kinetic parameters between sprinting and rebound jump, even if there was no relationship between performance variables (the sprint velocity and RJ index, both of which are described below).

Materials and Methods

Subjects. Sixteen male track and field sprinters and jumpers (age, 22.19 ± 1.11 years; height, 1.76 ± 0.05 m; and mass, 76.32 ± 5.06 kg) performed sprinting and rebound jump at maximal effort. They were screened for injuries that could affect sprinting and rebound jump performance. All subjects had performed sprinting and rebound jump in their training programs and were familiar with all experimental trials. The Ethics Committee for the Institute of Health and Sport Sciences, University of Tsukuba, Japan, approved all study procedures (approval number: 22-341).

Procedures. Data were collected at an outdoor track and field stadium. After warm-up, participants performed maximum-velocity sprinting and rebound jump at least twice. The rebound jump was performed first to eliminate the influence of fatigue caused by sprinting. Participants were videotaped in the sagittal plane with a high-speed video camera (EX-F1, 300 fps; Casio, Tokyo, Japan) positioned at the center of the running lane to the right of the 40-m mark. Ground reaction force was obtained using a one force platform (Kistler 9287B 0.9 m × 0.6 m; Kistler Instrumente AG, Winterthur, Switzerland; 9281A, 0.6 m × 0.4 m; 9281C, 0.6 m × 0.4 m; 1,000 Hz) for the rebound jump and three force platforms (9287B, 0.9 m × 0.6 m; 9281A, 0.6 m × 0.4 m; 9281C, 0.6 m × 0.4 m; 1,000 Hz) for sprinting.

For the rebound jump, participants wore their own training shoes (without spikes), which they usually wore during plyometric training. The rebound jump consisted of five repeated rebound-type jumps in the vertical direction with a double-leg takeoff from a standing position7,11,14,19). Participants were orally instructed to jump as high as possible and to minimize ground contact time. The trial with the highest RJ index (described in Data analysis) was selected for further analysis. This type of jump was considered the most suitable for testing our hypothesis because the ankle-joint kinetic parameters (joint torque and power) for this jump are the greatest for all types of rebound-type jumps, including rebound-type drop jumps from a height of 0.3 m and 0.5 m14). The interclass correlation coefficient for the RJ index in this study was 0.853 (P < 0.001).

For sprinting, all participants, who wore their own spiked shoes, performed 60-m sprints, consisting of a 30-m build-up followed by a timed “flying 30 m” over the force plate. A photocell timing system (Speed Trap 2, Brower Timing Systems, Draper UT, USA) was placed along the track with a beam located 10.0 m to either side of the center of the force plate. This system provided the athletes with immediate, split-time feedback to encourage competitiveness. A starting mark was used to allow the subjects to strike the force plate without altering their technique immediately before the plate. Based on previous testing sessions, the mark was located approximately 45 m before the force plate.

A trial was deemed successful if the athlete struck the force plate at maximum velocity without noticeably or consciously altering the stride pattern, as determined visually by the experimental observer. Although each subject made several attempts, some subjects achieved only 1 successful trial. Consequently, in an effort to collect all data within a reasonable time frame and avoid the potential confounding effect of fatigue, the study was limited to a single successful trial for some subjects20).

Data analysis. A 14-segment model comprising the hands, forearms, upper arms, feet, lower legs, thighs, head, and trunk was used. Reference markers were affixed to each of these body segments. In total, 23 body points (hands, wrists, elbows, shoulders, toes, first metatarsal bones, heels, ankles, knees, greater trochanters, head, ears, and the suprasternale) and four calibration markers were digitized using a Frame-DIAS system (DKH Co., Tokyo, Japan), starting from 10 frames prior to touch-down and ending at 10 frames after toe-off. All subsequent data analysis was undertaken using Matlab™ (v. 8.3.0, The Mathworks™, Natick, MA, USA). The raw coordinates were converted into real coordinates using four reference markers placed on the ground. The coordinates were smoothed by a Butterworth digital filter with optimal cut-off frequencies of 7.5 - 10.5 Hz, determined using the residual method31). For the kinetic inputs to inverse dynamic analysis, force platform data (1,000 Hz) were down-sampled to the sampling rate of the kinematic data (300 Hz).

In sprinting, horizontal velocity, step length, and frequency of a single step were calculated for each sprint trial using the information taken from the 300-fps camera. A step cycle was defined as the period from the moment of touchdown on the force plate by one foot until plate contact by the contralateral foot20). Velocity was defined as the horizontal velocity at the center of mass of the whole body at toe-off. Step length was calculated as the distance between toe points at the force plate after touchdown in two consecutive steps, and step frequency was calculated by dividing the velocity by the step length.

The RJ index for rebound jump, which indicates mechanical power per kg of body mass during take-off49), was calculated as follows7,11,19,23):

\[ RJ \text{ index} = \frac{\text{JH} \cdot \text{CT}^{-1}}{\text{body mass}} \]

where CT is the contact time and JH is the jump height. Contact time and flight time were calculated using vertical ground reaction force data (based on 3% of the body weight). Jump height was calculated using Bosco’s
The calculation and significance of the RJ index were identical to the reactive strength and reactive strength index\(^23,26\).

During sprinting and rebound jump, the location of the center of mass and inertia of each segment were estimated based on the body segment parameters for Japanese athletes, as described by Ace\(^27\). Joint torques were calculated using an inverse dynamics approach. Joint power was calculated as the dot product of joint torque and angular velocity. Extension and plantar flexion were denoted as positive at each of the three leg joints. To evaluate the joint torque and power output characteristics for a single leg during the rebound jump, the ground reaction force was divided in half, and these data were used to calculate the joint kinetic parameters.

The support phase (from the point of touchdown to toe-off) was divided into two parts\(^11,13\): the eccentric phase (from the point of touchdown to the lowest point of the body’s center of gravity) and the concentric phase (from the lowest point of the body’s center of gravity to toe-off). Moreover, mean ankle-, knee-, and hip-joint torque (eccentric and concentric phases) and mean ankle-, knee-, and hip-joint power (negative and positive values) were calculated using plantar flexion and/or extension joint torque only. In this study, mean negative hip power was not calculated, because negative hip power in terms of hip extension torque was not observed during sprint running. The time series data of all subjects were normalized to the time of the support phase (0 - 100%), and the mean values were noted.

**Statistical analysis.** Statistical analysis was conducted using SPSS (IBM SPSS Statistics Version 21, SPSS, Chicago, IL). The Shapiro-Wilk test was used to test for normal distribution. The mean values and standard deviations were calculated. The Pearson’s correlation coefficient was used to determine the relationships between variables during sprinting and rebound jump. Statistical significance was set at \( P < 0.05 \).

**Results**

For sprinting, the sprint velocity was 9.63 ± 0.46 m/s (range: 8.86 - 10.50), step-length was 2.20 ± 0.11 m (range: 2.06 - 2.49), and step-frequency was 4.39 ± 0.30 Hz (range: 3.84 - 4.80). For rebound jump, the RJ index was 3.246 ± 0.448 (range: 2.585 - 3.991), jump height was 0.502 ± 0.056 (range: 0.397 - 0.592), and contact time was 0.156 ± 0.014 s (range: 0.138 - 0.189). There was no significant correlation between sprint velocity and RJ index (Fig. 1). The sprint velocity and RJ index had normal distribution with the Shapiro-Wilk test (\( P = 0.927 \) and 0.567, respectively).

In Figs. 2 and 3, the mean joint torque and power values of the ankle, knee, and hip during sprinting were plotted against those for rebound jump. For mean joint torque, a significant correlation between sprinting and rebound jump was noted for the ankle and knee joints in both the eccentric and concentric phases. For mean joint power, significant correlations between sprinting and rebound jump were observed for the mean negative power of both the ankle and knee joints.

The patterns for ankle- and knee-joint angular velocity, joint torque, and power during sprinting were similar to those during rebound jump (Fig. 4). At the hip joint, large differences in joint angular velocity, joint torque, and power were observed between sprinting and rebound jump. During sprinting, the hip joint showed only extension; however, during rebound jump, the hip joint underwent flexion before extension. Joint angular extension velocity, positive joint torque, and positive hip-joint power were greater during sprinting than during rebound jump.

**Discussion**

We investigated the relationship between support-phase lower-limb joint kinetic parameters in sprinting and rebound jump. Ankle- and knee-joint kinetic parameters, especially in the eccentric phase, were correlated for sprinting and rebound jump, although there was no such correlation between sprint velocity and RJ index. Previous studies investigating the relationship of performance variables between sprinting (10 m\(^7\) and 60 m\(^3\) sprint time) and rebound jump (jump height\(^5\), average power\(^5\), and RJ index\(^3\)) have not shown any correlation, suggesting that rebound jump performance may not be important during sprinting\(^5\). However, despite this lack of correlation for performance variables (sprint velocity and RJ index in our study), our study suggests that there may be a mechanical similarity, which is important for understanding the determinants of sprinting performance and plyometric training that may improve sprint performance. Our hypothesis was partially supported, except that there was also a correlation between knee-joint kinetic parameters in sprinting and rebound jump.

There were significant correlations between sprinting and rebound jump for ankle- and knee-joint kinetic parameters, but not for hip-joint kinetic parameters (Figs. 2 and 3). Ankle plantar flexor and knee extensor muscles
Fig. 2  Relationships between sprint running and rebound jump for the mean joint torque during the eccentric and concentric phases.

Fig. 3  Relationships between sprint running and rebound jump for the mean negative and positive joint powers.
in sprinting and rebound jump stretched after touchdown and shortened at toe-off (Fig. 4). This pattern is called the stretch-shortening cycle movement\(^\text{28}\). Moreover, the patterns for joint torque and power of the ankle and knee joints during sprinting were similar to those during rebound jump, suggesting that the mechanical similarities between ankle plantar flexor and knee extensor muscle contraction may explain our observed correlation between ankle- and knee-joint kinetic parameters during sprinting and rebound jump. The hip joint during rebound jump showed a pattern identical to that of the other joints; however, in sprinting, the hip joint only showed extension. Further differences between sprinting and rebound jump were noted in terms of the magnitude of joint torque, joint power, and the pattern of joint power. These differences may explain the lack of a relationship between hip-joint kinetic parameters in sprinting and rebound jump as well as the lack of a relationship between sprint velocity and RJ index.

During sprinting, the ankle joint plays an important role in achieving high performance by producing a large vertical force\(^\text{15,16}\), reducing ground contact time\(^\text{17,18}\), and enhancing mechanical efficiency\(^\text{18}\), indicating that the ankle joint is important for sprinting performance. In rebound jump, performance (RJ index, jump height, and contact time) is known to be primarily affected by the ankle joint\(^\text{14}\). Moreover, ankle-joint functions that are important for sprinting (enhancing mechanical efficiency and reducing ground contact time), are also important for rebound jump\(^\text{14}\). Collectively, these results explain the significant relationship observed between ankle-joint kinetic parameters during sprinting and rebound jump.

In addition, a correlation was also noted between the knee-joint kinetic parameters of sprinting and rebound jump (Figs. 2 and 3). Although no previous study has reported the importance of the knee-joint kinetic parameters in rebound jump, knee-joint (knee extensor) function in drop jumping (in which ground contact time is not minimized) is crucial for regulating performance as a power source\(^\text{29}\) and affecting jump height due to greater energy production\(^\text{30}\). Thus, knee-joint function in rebound jump may also affect rebound jump performance, as with drop jumping. During the eccentric phase in sprinting, the knee joint plays an important role in regulating leg stiffness\(^\text{19}\) and energy absorption\(^\text{20}\). However, in sprinting, knee extension is not necessary for achieving a high velocity, because faster sprinters show less knee extension during the support phase\(^\text{31}\), which indicates that knee extension negatively affects sprint velocity\(^\text{32}\), and knee-joint torque does not contribute substantially to power generation during the latter part of the support phase\(^\text{22}\). However, we demonstrated a significant correlation between knee-joint
joint torque during the concentric phase in sprinting and rebound jump, which also may explain the lack of a significant relationship between sprinting and rebound jump performance.

Our results suggest that it is important to determine the factors contributing to sprint performance in order to investigate the relationships not only between performance variables, but also between joint kinetics variables. For applications to plyometric training, our results indicate that plyometric training using rebound jump may be useful for improving mechanical output of the ankle and knee joints during sprinting. However, plyometric training using rebound jump may increase knee extension from improved knee-joint mechanical output during the latter part of the support phase in sprinting, which may negatively affect sprinting performance. Future studies are therefore needed to test the effects of rebound jump on plyometric training, especially after taking our findings into consideration.

In conclusion, we demonstrated no relation between sprinting and rebound jump on plyometric training, especially in the eccentric phase of sprinting and rebound jump.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Acknowledgments

This study was partially supported by the 2014 Research Project of the Faculty of Health and Sport Sciences.

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