Radial Movements and Lower Limb Joint Kinematics during the Takeoff Phase of Kicking Pullovers

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The purpose of this study was to clarify the mechanisms and techniques of one-leg swing type takeoffs for acquiring vertical and angular momentums of backward rotation. The kinematics were measured for successful kicking pullovers performed by 12 adult males. Using a 12-segment rigid body link model, the contributions of each body parts to the vertical and angular momentums, the kinematics of both leg joints, and the accelerations of the body parts relative to hip joint of the support leg during the takeoff phase were calculated. The swing leg accelerated away from the ground during the takeoff phase, and was responsible for 64% of the vertical momentum and 43% of the angular momentum of the whole body at takeoff. The hip joint of the support leg extended to the limit of the range of motion at takeoff, achieving both an increase in ground contact time and a backward rotation of the trunk. We concluded that the swing leg greatly contributes to the acquirement of vertical and angular momentum of the whole body in one-leg swing type takeoffs including backward rotation. Specifically, swinging the swing leg using a large range of motion and fully extending the hip joint of the support leg hip joint are the two important technical elements to pre-tense the support leg muscles and increase the ground reaction impulse.

Keywords: kicking pullovers, takeoff, swinging, angular momentum, running jump

1. Introduction

Rotational movement in the air is an important technical element that influences the artistic performances of sports such as gymnastics and free-style skiing. Since the vertical and angular momentums about the center of mass (CoM) at the moment of takeoff largely determine the number of rotation and twists in the air (King and Yeadon, 2004), takeoff techniques to acquire these kinematics have been studied. Specifically, the angle of the whole body to the ground, the contributions of the body parts to the kinematics, the ground reaction forces (GRFs), and the joint torques were investigated on backward somersaults that were started from a standing posture (Brüggemann, 1983; Mathiyakom et al., 2006; Payne and Barker, 1976) or those held in tumbling (Hwang et al., 1990; Kerwin et al., 1998), in which both legs are aligned.

However, considering that the running jump allows human to achieve the highest jumping height and involves the swinging up of one leg and pushing of the ground by the other leg, the one-leg swing type takeoff may also be effective for acquiring vertical and angular momentums at takeoff. Indeed, there are several sports movements in which one-leg swing type takeoffs and approach velocity are utilized for rotation in the air. One representative example is the bicycle kick (overhead kick) used in soccer and Sepak Takraw. This technique requires a backward rotation of the whole body in the air to kick a ball overhead and fly backwards. The takeoff involves swinging of the leg that is not used for hitting the ball (Shan, 2008), and a forward movement of the whole body prior to the takeoff is observed.

Another example is the kicking pullover. A pullover (or upward circle) is one of the most basic techniques of gymnastics to mount a horizontal bar through backward rotation (American Sports Education Program and USA Gymnastics, 2009). It is classified into several patterns according to the height of the bar and the style of the takeoff (Turoff, 1991). The most introductory of them is accompanied by an approach of several steps and one-leg swing type takeoff, and is called...
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“kicking pullover”. According to Konosu et al. (2017), adult males have 1.1 m/s of vertical velocity and 0.6 Nms/kg of angular momentum about the CoM at take-off in successfully performed kicking pullovers. It was suggested that these kinematics assist the body to rise and rotate backward after the takeoff, facilitating the mounting on a bar.

As mentioned above, extensive technical analyses of the takeoff aiming at acquiring vertical and angular momentums with both legs aligned has been carried out (Hwang et al., 1990; Mathiyakom et al., 2006). On the other hand, for the bicycle kick and the kicking pullover, there is little information available on the technicalities of the takeoff. Mechanical analyses of these movements will clarify the roles and technical details of each body part, including the swing leg, and contribute to the establishment of a teaching method for one-leg swing type takeoffs involving rotational movement.

Since a kicking pullover is performed while holding on a bar, the approach distance and posture are controlled, the movement is easy to be restricted to the sagittal plane, and in addition, it is safe for the participants. Therefore, the kicking pullover is excellent as a model of mechanical measurement and analysis. In addition, the kicking pullover is one of the most important curriculums in physical education in elementary schools (Mohnsen, 2008). Clarifying its mechanisms and techniques will contribute to the establishment of a lifelong commitment to physical activity and advanced movement skills after adulthood (Gallahue et al., 2011).

For the concrete analysis of the kicking pullover, paying attention to the counter-movement and swinging will be effective in addition to basic biomechanical data such as the contributions of each body parts to the vertical and angular momentums (Brüggemann, 1983; Hwang et al., 1990) and the joint movements. Dapena and Chung (1988) projected the velocities of the CoM and the body parts to a vector going from the foot to the CoM during a running high jump. It was found that the CoM was directed toward the ground at touchdown, and that the swing leg and trunk forces the support leg to flex during the takeoff phase. These movements allow a high level of muscle activities of the support leg at the start of the push-off (pre-tensing) (Bobbert et al., 1996). An analytical method like this should be effective to reveal the mechanisms of the takeoff in kicking pullovers.

The purpose of this study was to clarify the mechanisms and techniques of one-leg swing type takeoff for acquiring vertical and angular momentums by mechanically analyzing kicking pullovers.

2. Methods

2.1. Participants

The participants were 12 healthy adult males (age: 24.8 ± 2.2 years; height: 1.72 ± 0.06 m; body mass: 65.7 ± 6.8 kg) who could successfully perform kicking pullovers. All of them had learned how to perform kicking pullovers in physical education class in their primary schools, although none had majored in gymnastics. This study was conducted with written consents from the participants under the approval of the research ethics committee of the university.

2.2. Protocols

The experiment was conducted using a horizontal bar set constructed at our laboratory. The height of the bar was set to 75% of each participant’s height (Konosu et al., 2017). The participants were instructed to successfully perform four kicking pullovers following a warming-up which included practicing kicking pullovers. All the trials were carried out barefoot at the participant’s own pace with overgrip hand. To induce natural movements, no specific instructions were given regarding the approach speed, posture, or foot placement. To prevent fatigue, the participants rested for at least one minute between each trials to prevent fatigue. All the participants successfully performed kicking pullovers in all the trials.

2.3. Measurements

The positions of 24 spherical markers attached to the body landmarks (Figure 1a) of the participants were recorded at 200 Hz using a motion capture system including 13 infrared cameras (Motion Analysis Corp., CA, USA). These data were then smoothed with a zero-lag, 4th order, Butterworth low-pass filter. The cut-off frequencies were determined to be 6.7-12.6 Hz using a residual analysis (Winter, 2009). Vertical GRF applied to the support leg foot was recorded at 2000 Hz with a force plate (9281B, Kistler, Winterthur, Switzerland).
2.4. Analyses

The target period of analyses was from the touchdown to the takeoff of the support leg foot (takeoff phase, Figure 1c). The timings of touchdown and takeoff were identified as the times when the vertical GRF of the support leg foot exceeded and fell below 10 N.

Sagittal plane motion analyses were performed (Figure 1b). The origin of the coordinate system was placed at the center of the bar. The vertical upward direction and the horizontal direction of the approach were taken as positive. Variables related to the rotation were shown with the backward rotation taken as positive and indicated by the angle with respect to the horizontal axis.

Kinematics were calculated using sagittal plane analyses with a 12-segment rigid body link model composed of head, trunk, bilateral forearm, bilateral upper arm, bilateral thigh, bilateral shank, and bilateral foot segments. The position and velocity of the CoM, the whole body angular momentum about the CoM (Robertson et al., 2013) were calculated. The ratios of the vertical and angular momentums of each body parts (head and trunk (HAT), bilateral arms, swing leg, and support leg) to the whole body at the takeoff were calculated as contributions. The inertial parameters of each body segment were calculated using the regression equation of Winter (2009).

Takeoffs in the jumps including approach velocity can be easily understood as a movement in which the whole body expands and contracts while rotating around the ground contact point. Therefore, the pivot motion around the support leg foot was analyzed based on Dapena and Chung (1988). The hinge position was calculated by the center of pressure of the GRF (Figure 1b). The vector from the hinge to the CoM was taken as “radial vector”, and its length and angle were defined as “radial distance” and “radial angle”, respectively. The radial distance quantifies the expansion and contraction of the whole body, and the radial angle indicates the ratio of contributions by the change in the radial distance to the vertical and horizontal movements.

Except for gravity and inertial forces, the forces to extend or flex the support leg applied through the hip
joint by each body parts can be estimated as the products of the mass and the acceleration along the radial vector. Therefore, the velocity and acceleration of the body parts relative to the hip joint of the support leg were orthogonally projected to the radial vector at each time point and expressed as the products of the mass:

\[ V_i = m_i \frac{\vec{v}_i \cdot \vec{r}}{|\vec{r}|} \]  
\[ A_i = m_i \frac{\vec{a}_i \cdot \vec{r}}{|\vec{r}|} \]

where \( m_i \) is the mass of the body part \( i \), \( \vec{v}_i \) and \( \vec{a}_i \) are the velocity and acceleration of the body part \( i \) with respect to the hip joint, and the \( \vec{r} \) is the radial vector. All variables were expressed as the means ± standard deviations of the participants, and the time series data were normalized by setting the entire takeoff phase as 100%. The whole-body angular momentum was normalized by the body mass. The position of the CoM and radial distance were normalized by the body height.

3. Results

3.1. Whole body movement and the contributions of specific body parts

Figure 2 shows the CoM movement and the rotational movement of the whole body. The horizontal velocity of the CoM was 1.36 ± 0.26 m/s at touchdown, and decreased to 0.28 ± 0.30 m/s at takeoff. The vertical velocity was −0.43 ± 0.13 m/s at touchdown, and increased to 1.09 ± 0.14 m/s at takeoff. The angular momentum of the whole body about the CoM increased from 0.25 ± 0.06 Nms/kg at touchdown to 0.62 ± 0.08 Nms/kg at takeoff.

Figure 3 shows the contributions of the body parts to the vertical and angular momentums of the whole body at takeoff. The swing leg accounted for about 64% of the vertical momentum. The angular momentum of the whole body was roughly divided by the HAT (38%) and swing leg (43%).

![Figure 2](image-url) Movement of the whole body during the takeoff phase. The definitions of the coordinate systems are shown in Figure 1b. Ensemble averages and standard deviations are shown. (a) Position (upper row) and velocity (middle row) of the center of mass, and ground reaction force (bottom row). The position of the CoM was normalized by the body height. (b) Rotational movement of the whole body. The rotation angle was formed between the vector direction from the shoulder to the center of mass and the horizontal axis.
3.2. Lower limb joint kinematics

Figure 4 shows the angles and angular velocities of the joints of the lower limb. The hip joint of the swing leg was extended to 192° ± 8 deg at touchdown. Subsequently, it accelerated at an angle in the flexion direction in the first half of the takeoff phase, and kept about 250 deg/s in the second half. The knee joint of the swing leg flexed in the first half of the takeoff phase due to the flexion angular velocity which maximized to −347° ± 107 deg/s immediately after touchdown.

The ankle and knee joints of the support leg had flexion phases followed by the extension phases. On the other hand, the hip joint of the support leg continued to extend throughout the takeoff phase to reach 205° ± 9 deg at takeoff. The maximum extension angular velocities of the ankle (397° ± 63 deg/s) and hip joints (359° ± 71 deg/s) were larger than that of the knee joint (138° ± 57 deg/s).

3.3. Radial movements

Figure 5a shows the radial movement of the CoM. The radial distance decreased by 0.023 ± 0.015 m/m in the first half of the takeoff phase, and increased by 0.039 ± 0.011 m/m in the second half. The radial angle was 119° ± 5 deg at touchdown and 114° ± 5 deg at takeoff.

Figure 5b shows the velocities and accelerations of each body parts relative to the hip joint of the support leg orthogonally projected to the radial vector (shown as the products of masse of each body parts). The velocity and acceleration of the swing leg was directed away from the ground throughout the takeoff phase. On the contrary, the velocity and acceleration of the HAT were directed towards the ground throughout the takeoff phase.

3.4. Ground reaction force and impulse

The GRF on the support leg is shown in Figure 2a. The vertical component was 2.59 ± 0.35 BW at maximum, and the vertical impulse over the takeoff phase was 2.81 ± 0.46 Ns/kg. The horizontal component of the GRF was −0.87 ± 0.24 BW (backward direction) at maximum, and was in a forward direction immediately after touchdown.

4. Discussion

In this study, the takeoff phase of kicking pullovers was analyzed to clarify the mechanisms and techniques of one-leg swing type takeoff including backward rotation. The vertical GRF of approximately 2.6 BW is almost the same as that reported in a previous study (Konosu et al., 2017) and is much larger than 0.4 BW, the vertical reaction force from the bar to the hands at takeoff reported in that study. Therefore, although both GRF and reaction forces from the bar act on the body during the takeoff phase, it is likely that techniques suitable for increasing GRF have been adopted by the participants, and that the takeoff mechanisms and techniques observed in this study are similar to those of other one-leg swing type takeoffs including backward rotation.

The velocity of the CoM was directed forward and downward at touchdown (Figure 2a). The radial distance decreased due to this velocity in the first half of the takeoff phase, and increased in the second half (Figure 5a). The ankle and knee of the support leg, which determine the length of the support leg (toe to hip), flexed and extended synchronously with this length (Figure 4). These data may suggest that the approach velocity in kicking pullovers acts as a counter-movement which pre-tenses the extensor muscles around support leg joints and reuses the kinetic energy of the whole body at touchdown, as it has been observed in running jumps (Bobbert et al., 1996; Dapena and Chung, 1988).
Accelerations of each body parts with respect to the hip joint of the support leg during the takeoff phase can promote the above-mentioned pre-tensing of the support leg muscles and the increase in the GRF impulse (Cheng et al., 2008; Dapena and Chung, 1988). In this study, the swing leg accelerated away from the ground throughout the takeoff phase (Figure 4, 5b), suggesting that this leg largely contributed to the pre-tensing of the support leg muscles and GRF impulse. In addition, this leg was responsible for the major part of the vertical and angular momentums of the whole body at the takeoff (Figure 3). It was the angular velocity of approximately 250 deg/s of the swing leg hip joint after the middle of the takeoff phase (Figure 4) that allowed these contributions. In order to swing the leg so fast and for a long time, directing the swing leg downward at touchdown is necessary to acquire a large range of swinging (Figure 1c). On the other hand, the body was tilted backwards at touchdown (Figure 1c, 5a). Such a body tilt is common in other jumps that utilize the approach speed (Hwang et al., 1990; Kerwin et al., 1998). In addition, in the kicking pullover, it plays a role in sinking the lower body under the bar to achieve backward rotation. To
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make tilting of the trunk backward and directing the swing leg downward compatible, hip joint needs to be extended largely at takeoff. The maximum angle of the hip joint was around 190 deg in previous studies (Boone and Azen, 1979; Roaas and Andersson, 1982), indicating that the maximum range of motion was used in this study (Figure 4).

On the contrary, the HAT accelerated to the ground during most of the takeoff phase (Figure 5b). This is because the HAT was parallel to the radial vector at touchdown, and then rotated backwards while the support leg is in contact with the ground (Figure 1c). The same tendency of acceleration was observed in the upper limbs (Figure 5b) which extend along with the movement of the upper part of the HAT (Figure 1c). These results suggest that the HAT and upper limbs made negative contributions to the pre-tensing of the muscles of the support leg and the GRF impulse by adding a force to extend the support leg. This is the opposite result to the running jumps (Dapena and Chung, 1988). Since the HAT plays an important role in angular momentum which is one of the objectives of kicking pullover takeoff (Figure 3), in exchange, the negative contribution could not be avoided.

The joint movements of the support leg can be explained from the perspective of increase in the ground contact time and the resulting GRF impulse. In this study, the angle of the hip joint at takeoff exceeded 190 deg (Figure 4), which is the maximum angle of the hip joint reported in the previous studies (Boone and Azen, 1979; Roaas and Andersson, 1982). As shown in Figure 6, the trunk was twisted and the pelvis was at an angle on the frontal plane such that the side of the swing leg was high and the side of the support leg was low. Therefore, the hip joint seems to have been abducted in addition to being fully extended. These extension and abduction achieved both an increase in ground contact time and a backward rotation of the trunk (Figure 1c). The angle is larger than in running jumps that do not include backward rotation (Ae et al., 2008). In the takeoff of tumbling, as the posture in the air extends, and as the requirement of the angular momentum of the whole body at takeoff increases, the hip joint angle at takeoff increases (Kerwin et al., 1998). When integrating these findings, the extension of the hip joint of the support leg towards the takeoff is a technique that becomes more important as the requirement of backward rotation increases.

Consistent with the hip joint, the extension of the support leg ankle joint is effective for upward movement and backward rotation of the whole body (Figure 1c). However, for the knee joint of the sup-
port leg, extension is required for the upward movement of the body, whereas flexion is required for the backward rotation of the support leg thigh accompanied by backward rotation of the trunk. It is probably due to these two effects cancelling out each other that the knee joint did not show such a large extension in angular velocity as the hip or ankle joint (Figure 4). Indeed, in running jumps that do not include rotation, the knee joints exhibit peak extension of angular velocities comparable to those of the ankle and hip joints (Muraki et al., 2008).

Although in this study we focused on the kinematics, further kinetic analyses will be required in future to understand the mechanisms of acquiring angular momentum. The support leg hip and knee joints had extension and flexion angular velocities at touchdown, respectively (Figure 4). This movement is like pulling the swing leg toward oneself and hitting it to the ground, and increase the forward component of the GRF (Figure 2a) and moment about the CoM after touchdown. These results coincides with Mathiyakom et al. (2006) who has compared the takeoff in jumps with and without backward rotation from a standing posture. In their study, the jump with backward rotation needed larger hip extension torque and smaller knee extension torques than the jump without backward rotation, and these differences were caused by the activities of biarticular muscles of the joints. Further research on kicking pullovers focusing on joint torques, muscle activities of both leg joints, and the control of the GRF direction resulting therefrom are necessary.

In this study, the participant selection criteria was the ability to “successfully perform kicking pullovers,” and none of the actual participants had majored in gymnastics. Therefore, our data seem to represent the minimum techniques required to achieve kicking pullovers. In contrast, to establish specific teaching methods that are useful in sports and physical education, the grouping of movements by successful and unsuccessful or by skill level and finding differences between them are effective, which are the important issues for the future. The mechanisms of kicking pullovers discussed here will be foundations in such comparative studies in the future.

5. Conclusions

It was found that the swing leg greatly contributes to the acquirement of vertical and angular momentums of the whole body in kicking pullovers. This leg can pre-tense the support leg muscles by adding a force to flex the support leg and is responsible for the major part of the vertical and angular momentums of the whole body. Thus, swinging the leg using a large range of motion is an important technique. Also, extending the hip joint of the support leg maximally towards the takeoff is an important technique to achieve both increase in ground contact time and backward rotation of the trunk. The findings in this study will serve as the basis for the mechanisms and techniques of the other one-leg swing type takeoffs including backward rotation.

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