Relationship between Ground Reaction Force and Kinetics of Both Legs in Kicking Pullovers:
Kinetics of Single-leg Takeoff for Backward Rotation

Running title
Kinetics during the Takeoff Phase of Kicking Pullovers

Authors
Akira Konosu*, Shinsuke Yoshioka¹, and Senshi Fukashiro²

Affiliation
¹ Graduate School of Arts and Sciences, The University of Tokyo, 3-8-1, Komaba, Meguro-ku, Tokyo, 153-8902 Japan
² Japan Women’s College of Physical Education, 8-19-1 Kitakarasuyama, Setagaya-ku, Tokyo, 157-8565 Japan

E-mail address
konosu@idaten.c.u-tokyo.ac.jp (Akira Konosu)
Abstract

In this study, we analyzed the relationship between the ground reaction force (GRF) and both leg kinetics in kicking pullovers, with the aim of clarifying the mechanics and techniques for acquiring vertical GRF and moment in single-leg takeoffs for aerial rotation. GRF applied to the support leg foot and kinematics were recorded for the takeoff phase of successful kicking pullovers by 11 adult males. Using a 12-segment, sagittal-plane rigid body link model, the relationship between GRF and kinetics of both legs were analyzed. Although the GRF had its peak in the middle of the takeoff phase, it also contributed to the generation of the moment around the center of mass (CoM) by being tilted forward than to the CoM immediately after touchdown and before takeoff. The support leg was struck against the ground with angular velocities and torques of the hip extension and knee flexion at touchdown. The swing leg accelerated forward in the first half of the takeoff phase. These movements probably contributed to tilt the GRF forward immediately after the touchdown. The torque waveforms of the support leg joints were, on the whole, similar to those in the high jumps. It is suggested that in single-leg takeoffs for aerial rotation, controlling GRF direction with both leg movements while increasing the peak GRF with the takeoff techniques common to running jumps is an efficient strategy to acquire vertical GRF and moment with limited leg strengths.

Keywords: Kicking pullover, Takeoff, Backward rotation, Swinging, Ground reaction force control
1. Introduction

Rotation in the air is one of the most important movement components in sport activities that evaluate artistry such as gymnastics and ski/snowboard. In order to rotate in the air as many times as possible and land reliably, it is necessary to acquire large and appropriate ratio of vertical momentum of the whole body and angular momentum around the center of mass (CoM) during the takeoff (Brüggemann, 1983; Hwang et al., 1990; Cheng et al., 2008). To date, techniques for acquiring these momentums have been analyzed mainly focusing on the takeoffs in the tumblings (Kerwin et al., 1998; Hwang et al., 1990) and in backward somersaults or flick-flac started from a standing position (Brüggemann, 1983; Payne and Barker, 1976; Mathiyakom et al., 2006), in which both legs are aligned and in contact with the ground during the takeoff. However, single-leg jumps are also widely used for aerial rotation. For example, in a bicycle kick (overhead kick), a swinging of the leg that is not the side to kick the ball is observed (Shan, 2008), suggesting that swinging is involved in the acquisition of whole body momentums. A swinging is also observed in the accelerator jump of figure skate, suggesting that it can contribute to the angular momentum around the axes in various directions.

Single-leg jumps often follow approaches, having mechanical and physiological advantages over the jumps started from a standing position. Firstly, in the running high jumps, the CoM has a velocity component toward the ground at touchdown (Dapena and Chung, 1988). As well as in countermovement, this velocity promotes pre-tension (Bobbert et al., 1996; Harman et al., 1990) and causes stretch reflex of the support leg extensors (Jones and Watt, 1971; Dietz et al., 1979), augmenting the vertical ground reaction force (GRF) impulse in the takeoff phase and being reused as kinetic energy after the takeoff (Asmussen and Bonde-Petersen, 1974). It is suggested that in the single-leg jumps for aerial rotation, while taking these advantages and acquiring large GRF, vertical and angular impulse of the GRF are appropriately adjusted by controlling the GRF direction.
Secondly, swinging arms or a leg generally apply forces in the opposite direction to the other parts of the body, and promotes the muscle contraction of the support leg extensors and the contact time to the ground, augmenting vertical GRF impulse (Feltner et al., 1999; Feltner et al., 2004; Hara et al., 2006; Cheng et al., 2008; Lees et al., 2004; Harman et al., 1990; Shetty and Etnyre, 1989). Although the mechanisms by which the swinging augments the jump performance have been studied mainly focusing on the vertical jumps, Cheng et al. (2008) has revealed that a larger angular momentum around CoM is acquired when there is an arm swinging in a simulation of backward somersault using a springboard. In addition, according to Ashby and Heegaard (2002), the swinging not only contributes to the production of vertical GRF impulse but also to the adjustment of the horizontal GRF impulse and the resulting angular momentum around the CoM in standing long jumps. Therefore, in single-leg jumps for the aerial rotation, the swing leg may help acquiring angular momentum by accelerating in the horizontal direction.

In order to clarify the mechanics and techniques to acquire vertical and angular momentums in the single-leg jump for aerial rotation, it is necessary to analyze the relationship between the GRF and kinetics of both legs. Kicking pullover (forward upward circling), one of the basic technique of horizontal bar in gymnastics, has been attracting attention in recent years as one of the representations of the single-leg takeoffs for vertical and angular momentums (Konosu et al., 2020). According to previous studies on kicking pullovers (Fukushima and Yamamoto, 1992; Konosu et al., 2017; Michitsuji et al., 2001), the CoM moves vertically upwards after the takeoff owing to small horizontal bar reaction force (BRF) after the takeoff, and vertical momentum at the takeoff greatly contributes to this movement. In addition, the effect of the BRF on the angular momentum around the CoM is small after the takeoff, and the body is rotated by maintaining the angular momentum which is acquired during the takeoff phase. The GRF is sufficiently larger than the BRF during the takeoff phase, indicating that the acquisition of vertical and angular momentum mainly depends on the technique of the legs. In addition, holding the horizontal bar has the advantage that the movement is easy to be confined to the
sagittal plane. These characteristics of the kicking pullover make it a suitable model to study single-leg takeoffs for aerial rotation, despite the interference of the BRF.

Although a previous study (Konosu et al., 2020) quantified the contributions of body segments to the vertical and angular momentums in the takeoff phase of kicking pullovers, understanding the details of the techniques and mechanisms requires investigation including kinetics. Since kicking pullovers are adopted in primary education programs, it allows children or non-gymnasts to safely challenge aerial rotation with the support by the bar (Mohlsen, 2008; Konosu et al., 2020). Therefore, the investigation would directly encourage ordinary people and sports beginners to learn how to takeoff with both legs for aerial rotation.

In this study, we investigated the relationship between the GRF and both leg kinetics during the takeoff phase of kicking pullover, with the aim of clarifying the mechanics and techniques for acquiring vertical GRF and moment around the CoM in single-leg takeoffs for aerial rotation.

2. Methods

2.1. Experimental protocol

The participants were 11 healthy adult males (age: 24.8 ± 2.3 years; height: 1.72 ± 0.06 m; body mass: 66.3 ± 6.5 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. This study was conducted with written consents from the participants under the approval of the research ethics committee of the university.

The experiment was performed using a horizontal bar set constructed in the 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 including practicing of kicking pullovers. All the trials were carried out barefoot at the participant’s own pace with overgrip hand. To induce natural movements, the main task was to make successful kicking pullovers, and no specific instructions were given regarding the approach speed, posture, or foot placement. 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.

2.2. Measurements and data processing

The positions of 24 spherical markers attached to the body landmarks (Konosu et al., 2020) of the participants were recorded at 200 Hz using a motion capture system including 13 infrared cameras (Motion Analysis Corp., CA, USA). The data were then smoothed with a zero-lag, 4th order, Butterworth low-pass filter. Using a residual analysis (Winter, 2009), the cut-off frequencies were determined to be 7-19 Hz. Horizontal and vertical GRFs applied to the support leg foot were recorded at 2000 Hz with a force plate (9281B, Kistler, Winterthur, Switzerland), and were synchronized with the marker position data in the motion capture system.

2.3. Analyses of kinematics and kinetics

The target period of analyses was from the touchdown to takeoff of the support leg foot (takeoff phase, Figure 1a). These timings were determined as the first frame when the vertical GRF first exceeded 5N and the last frame when it was lower than 5N.

Sagittal plane motion analyses were performed using a 12-segment rigid body link model composed of head, trunk, bilateral forearm, bilateral upper arm, bilateral thigh, bilateral shank, and bilateral foot segments (Figure 1b). The origin of the coordinate system was placed at the center of bar. The vertical upward direction and the horizontal direction of the approach velocity were taken as positive. Variables related to the rotation were defined with the backward rotation taken as positive and indicated by the angles with respect to the horizontal axis. The inertial parameters of each segments were calculated using a regression equation of Winter (2009). Based on the CoM of each segment, kinematics of the whole-body CoM and swing leg and the moment of the GRF around the whole-body CoM were calculated. The horizontal bar was tend to be gripped with the both hands distanced wider than the trunk width in order to pull the trunk to the bar, and the upper arm segments slightly deviated from the sagittal plane. However,
because the CoM of each segment was calculated from the marker positions located at both ends of the segments, the sagittal-plane coordinates of the CoM and the resulting kinematics were not affected by the deviation.

The torques of the three joints in both legs were calculated with inverse dynamics (Winter, 2009) using the GRF data smoothed by the Butterworth low-pass filter with the cutoff frequency of 15 Hz, which was determined as a close number to the frequency for the smoothing marker positions (Bezodis et al., 2013).

In swing motion, acceleration of the swing leg relative to the hip joint changes the reaction force to the trunk. This force change is estimated as the product of the relative acceleration of the CoM of the swing leg with respect to the hip joint and the mass of the swing leg. It is expected that the downward component of this force change increases the impulse of the vertical GRF, and the tangential component around the whole-body CoM increases the angular impulse of the GRF in the takeoff phase. To investigate these effects, the Product of the relative Acceleration of the Swing leg CoM with respect to the swing leg hip joint and the Swing leg mass (PASS, shown in BW units by dividing by the whole-body weight) and the tangential component of the PASS around the whole-body CoM were calculated using the following formulas:

\[
\text{PASS} = (a_{\text{swing}} - a_{\text{hip}})m_{\text{swing}}/(m_{\text{whole}}g) \\
\text{PASS}_{\text{tan}} = (R \frac{r}{|r|}) \cdot \text{PASS}
\]

where \(a_{\text{swing}}\) was the acceleration of the CoM of the swing leg (the collection of thigh, shank, and foot), \(a_{\text{hip}}\) was the acceleration of the swing leg hip joint, \(m_{\text{swing}}\) was the mass of the swing leg, \(m_{\text{whole}}\) was the mass of the whole body, \(g\) was the magnitude of gravitational acceleration, \(r\) was the vector from the whole-body CoM to the swing leg CoM, and \(R\) was the rotating matrix of 90°.

For plotting the time series data, the averages ± standard deviations of the data between the participants were calculated for each normalized time. The entire takeoff phase was taken as 100% (Figure 1a). To report the peak value of the parameters, the peak in the takeoff phase was
calculated for each trial, and the average ± standard deviation between the participants was calculated. Since the peak timings differ by trial, the averaged peak values may not correspond to the peak values in the time series graph.

2. 4. Simulation of the support leg joint torques

Based on the measured joint positions of the support leg and the center of pressure (CoP) of the GRF, the relationship between the direction of the GRF and the torques exerted by the support leg joints against the GRF was simulated. Throughout the takeoff phase, the effect of the change in the GRF angle on the moment arm of the GRF around each joint seemed significantly larger than the effect of the change in the positional relationship between the CoP and each joint (Figure 2c, e). Therefore, we primarily focused on the torques that the support leg joints had to exert against a GRF of 1 N with the angle of the GRF as a parameter using the following formula:

\[ T_i(\theta) = r_i \times e(\theta) J_i \quad (i = \text{hip, knee, ankle}) \quad \text{Eq. (3)} \]

where \( r_i \) was the vector from joint i to the CoP averaged over the entire takeoff phase and the participants, \( e(\theta) \) was a unit vector whose angle was \( \theta \) (the definition of angle is indicated in Figure 1b as “Angle of ground reaction force”). \( J_{\text{hip}} \), \( J_{\text{knee}} \), and \( J_{\text{ankle}} \) were 1, -1, and 1, respectively. When \( T_i(\theta) \) was directed right and left, each joint had to exert extension and flexion torques, respectively, to resist the GRF.

Second, the torque the hip joint had to exert against the GRF, with the time of the takeoff phase and the angle of the GRF as parameters, was calculated:

\[ T_i(t, \theta) = |r(t) \times (e(\theta) F(t))| \quad \text{Eq. (4)} \]

where \( t \) was the normalized time defined in Figure 1a, with the beginning and end of the takeoff phase 0 and 100, respectively, \( r(t) \) and \( F(t) \) were the vector from the hip joint to the CoP and the magnitude of the GRF at each normalized time averaged over the participants, respectively, and \( e(\theta) \) was a unit vector whose angle was \( \theta \).
3. Results

3.1. Ground reaction force and moment

The GRF and its horizontal and vertical components showed an arch shape with the peaks in the middle of the takeoff phase (Figure 2a, b). The peak values were $2.71 \pm 0.39$, $-0.88 \pm 0.24$, and $2.60 \pm 0.37$ BW, respectively. The horizontal component was in a forward direction immediately after touchdown and before takeoff. The angle of the GRF was $72 \pm 13$ deg at the touchdown frame, and after tilting backward to a maximum of $113 \pm 5$ deg in the middle of the takeoff phase, it tilted forward again to $64 \pm 16$ deg at the takeoff frame (Figure 2c, e). The moment of the GRF around the CoM maintained a value equivalent to the peak for a long period during the takeoff phase (Figure 2d).

3.2. Kinetics of the support leg joints

Figure 3 shows the angular velocities and torques of the support leg joints. The knee and ankle joints had flexion angular velocities in the first half of the takeoff phase and extension angular velocities in the second half. The hip joint had an extension angular velocity through the takeoff phase. At the touchdown, the hip joint had an angular velocity of $157 \pm 66$ deg/s and the knee joint had an angular velocity of $-210 \pm 93$ deg/s.

The hip, knee, and ankle joints exhibited peak extension torques of $0.312 \pm 0.047$, $0.243 \pm 0.104$, and $0.265 \pm 0.049$ BW·m, respectively. The peak timings of the knee and ankle joints were in the middle of the takeoff phase, while that of the hip joint was in the first half. The knee joint exerted flexion torque immediately after touchdown.

3.3. Kinetics of the swing leg

We then analyzed the movements of joints and CoM of the swing leg (Figures 4 and 5). The trajectory of the CoM showed different outlines between the first half and the second half of
the takeoff phase (Figure 5a). In the first half, the CoM moved linearly, and the direction of acceleration almost coincided with the direction of movement. Because of a hip flexion torque with a maximum of \(-0.221 \pm 0.032\) BW \cdot m and PASS (Product of the relative Acceleration of the swing leg CoM with respect to the Swing leg hip joint and the Swing leg mass, Eq. [1]) with a maximum of \(0.56 \pm 0.11\) BW in the first half of the takeoff phase (Figures 4 and 5), the hip flexion angular velocity reached \(-364 \pm 70\) deg/s, and the relative velocity of the swing leg CoM with respect to the hip joint reached \(2.70 \pm 0.41\) m/s at the middle of the takeoff phase (Figure 5b). The peak of \(\text{PASS}_{\text{tan}}\) (tangential component of PASS, Eq. [2]) was \(0.56 \pm 0.12\) BW (Figure 5c).

In the second half of takeoff phase, on the other hand, the CoM of the swing leg moved as a circle around the hip joint, with small angular velocities of the knee and ankle joints (Figure 4). Although the hip flexion torque was smaller than in the first half, the CoM moved as a circle around the hip joint with the velocity acquired in the first half, accelerating in the centripetal direction. The peak of the vertical component of the PASS was \(0.38 \pm 0.07\) BW (Figure 5c).

3.4. Simulation of the support leg torques

Since salient changes in the GRF angle were observed after touchdown and before takeoff, we simulated the relationship between the GRF angle and joint torques of the support leg using measured data. Tilting the GRF forward (decreasing the angle) required hip and ankle extension torques and knee flexion torque, especially a large hip torque (Eq. [3]; Figure 6a). Then, using the measured value of CoP, the position of hip joint and GRF at each time in the takeoff phase, the hip torque required to set the GRF angle to an arbitrary value was calculated (Eq. [4]; Figure 6b). The hip joint had to exert an extension torque of \(1.40\) BW \cdot m in order for the GRF angle to be 72 deg (the average of the participants at touchdown) at 50% normalized time, when the magnitude of GRF reached near maximum (Figure 2b). This was significantly larger than the actual peak torque of \(0.312\) BW \cdot m.
4. Discussion

In this study, we analyzed the takeoff phase of kicking pullover as an example of single-leg takeoff for aerial rotation. While the magnitude of the GRF showed an arch shape with the peak in the middle of the takeoff phase, while the moment around the CoM maintained a value equivalent to the peak for a long period. In particular, the GRF tilted forward than to the CoM immediately after touchdown contributed to this moment. At the moment of touchdown and immediately thereafter, the support leg had angular velocities of hip extension and knee flexion, and the swing leg accelerated forward.

The waveforms of the support leg joint torques (Figure 3) are similar to those of the running jumps not including rotation (Stefanyshyn and Nigg, 1998). First, the hip extension torque peaked at the beginning of the takeoff phase and then decreased linearly toward the takeoff. Second, the knee extension torque peaked in the middle of the takeoff phase and was small in the initial and terminal stages of the takeoff phase. In addition, flexion torque was exhibited at the initial stage. Finally, the ankle extension torque peaked at a timing slightly after the middle of the takeoff phase. Therefore, the leg extension techniques used for single-leg takeoff seem same in the basic part regardless of whether or not it includes rotational movement. The above-mentioned characteristics of the torque waveform are not observed in backward somersault without an approach velocity, suggesting that the techniques are particular to the takeoff utilizing approach velocities.

In order to acquire angular momentum around the CoM, the GRF has to be tilted forward than to the CoM (Prassas et al., 2006), which requires the support leg joints to exert the torques resisting the forward GRF (Mathiyakom et al., 2006). As shown in Figure 6a, the hip joint, located the most distal to the CoP among the three joints, has to exert especially large extension torque to resist the GRF. If the direction of the GRF was constant during the takeoff phase, the hip extension torque to be exerted in the middle stage, when the GRF reaches peak, will be significantly large (Figure 6b). Since the hip joint is close to the CoM (Figure 2e), the torque that the joint has to exert against the GRF can be estimated as the moment of GRF around the
CoM. Therefore, we estimated the moment using the participant-average data under the assumption that the GRF angle was constant (the moment arm was constant). First, the measured angular impulse of the GRF through the takeoff phase (Figure 2d) was divided by the integrated value of the measured GRF (Figure 2b), which resulted in 0.21 m of the moment arm. Then, this moment arm was multiplied by the measured GRF at the 35% takeoff phase, when the hip extension torque peaks (Figure 3). As a result, the moment was estimated to be 0.47 BW·m, which is 0.17 BW·m larger than the measured moment at this timing (Figure 2d). Therefore, fluctuating the GRF angle as the result (Figure 2c) contributed to reducing the peak hip joint. That is, tilting the GRF largely forward than CoM in the early and late stages and tilting it mildly in the middle stage during the takeoff phase is effective to reduce the peak hip joint torque. This requires techniques to quickly change the GRF direction. In conclusion, quickly controlling the GRF direction while utilizing a large peak GRF acquired with the takeoff techniques common to running jumps is an efficient strategy to maximize vertical and angular impulse with limited leg joint strengths.

At the touchdown frame, the hip and knee joints of the support leg had angular velocities and exerted torques of extension and flexion, respectively (Figure 3), which is an action like pulling the support legs toward participants themselves. That is, the collision of the support leg with the ground by the backward velocity contributed to the acquisition of forward GRF and the resultant moment around the CoM at touchdown and the subsequent period (Figure 2). Previous research (Prassas et al., 2006) has stated that one of the most general principal of acquiring angular momentum in gymnastics is the friction between the legs and the ground caused when suddenly putting the foot on the ground while one has an approach velocity. Combining this and our findings, for takeoffs including approach velocity, the horizontal GRF generated by colliding the foot with the ground universally plays a large role in the acquisition of angular momentum.

The swing leg accelerated forward in the first half of the takoff phase (Figure 4a), and this acceleration seems to have significantly contributed to tilting the GRF forward. The reduction
in distance between the hip joint and CoM due to the maximum flexion angular velocity of -510 ± 136 deg/s in the knee joint (Figure 4) allowed the linear trajectory of the swing leg CoM. Since the CoM of the swing leg was located below the CoM of the whole body, the forward acceleration of the swing leg CoM corresponds to an angular acceleration of backward rotation around the whole-body CoM. Just as a swinging accelerates the part other than the swing part in the opposite direction and decreases extension velocities of the leg joins in vertical jumps (Feltner et al., 1999; Feltner et al., 2004; Lees et al., 2004; Hara et al., 2006), this angular acceleration would delay the backward rotation of the parts other than the swing leg, decreasing angular velocities of support leg joints required to rotate the whole body (Figure 3). These changes augment the backward angular impulse of the GRF around the CoM through prolonging the ground contact time and changing the force-velocity relationship of the muscles in the support leg extensors (Hill, 1922). Therefore, our results (Figure 5) suggest that the swinging largely contributes not only to the acquisition of vertical momentum but also to the angular momentum in the takeoffs for aerial rotation.

In this study, we studied the techniques of backward rotation, that is, rotation around the left-right axis. However, in sport activities including techniques of aerial rotation as gymnastics, snowboard, and figure skate, there are also rotation techniques around the longitudinal and anteroposterior axes (twist and tilt, respectively) (Yeadon and Kerwin, 1999), and combining those elements increases the values of the techniques. When a person stands vertically on the ground, horizontal GRFs can largely contribute to these rotations. That is, the GRF in the left-right and anteroposterior directions contributes to rotation on the anteroposterior and longitudinal axes, respectively. Therefore, techniques controlling GRF direction with movements such as collision of the support leg to the ground and swinging a leg observed in this study may be used for the rotation around these axes. It is an important future issue to clarify the relationship between the GRF and kinetics of both legs in takeoffs for those rotations.

This study focused on the vertical force and moment from the ground during the takeoff phase, but the BRF should also partly contribute to those. The vertical component of the BRF
produces vertical momentum, and the backward component produces backward angular momentum, since the CoM is below the horizontal bar (Figures 1a and 2c). The elbow and shoulder joints have to exert extension torques to resist these force components, and it has been reported that torques are exerted at the takeoff in that direction (Konosu et al., 2017). Fluctuation in the BRF during the takeoff phase is probably not as rapid as in the GRF (Figure 2a, b), as the hands are always gripping the bar. However, owing to the acceleration of the swing leg (Figure 5), the BRF may fluctuate in synchrony with the GRF to a certain extent. Movements to enhance pre-tension and stretch reflexes of the elbow and shoulder muscles would also cause fluctuations in the BRF. Therefore, the direction of the BRF may be controlled to avoid an increase in the peak torques of the elbow or shoulder joints, as with the hip joint in this study. Techniques for controlling the BRF during the takeoff phase will be an interesting research topic in the future.

5. Conclusion

In this study, we analyzed the relationship between GRF and both leg kinetics during the takeoff phase of kicking pullovers, with the aim of clarifying the mechanics and techniques for acquiring vertical GRF and moment in single-leg takeoffs for aerial rotation. Although the GRF applied to the support leg had its peak in the middle of the takeoff phase, it was largely tilted forward than to the CoM immediately after touchdown and before takeoff to contribute the angular impulse around the CoM. The support leg was struck against the ground with the angular velocities and torques of the hip extension and knee flexion at touchdown, and the swing leg accelerated forward in the first half of the takeoff phase. These movements contributed to tilt the GRF forward immediately after the touchdown. Since the torque waveforms of the support leg joints were in many ways similar to those of the high jump, it is concluded that controlling GRF direction with both legs while increasing the peak GRF with the techniques common to running jumps is an efficient strategy to acquire vertical GRF and moment with limited leg joint strengths. It will be an important issue to verify whether similar
techniques are used in the takeoffs for aerial rotation around the longitudinal and anteroposterior axes.
References

Ashby, B. M. and Heegaard, J. H. (2002). Role of arm motion in the standing long jump. J. Biomech., 35: 1631-1637.

Asmussen, E. and Bonde-Petersen, F. (1974). Storage of elastic energy in skeletal muscles in man. Acta physiol. Scand., 91: 385-392.

Bezodis, N. E., Salo, A. I., and Trewartha, G. (2013). Excessive fluctuations in knee joint moments during early stance in sprinting are caused by digital filtering procedures. Gait Posture, 38: 653-657.

Bobbert, M. F., Gerritsen, K. G., Litjens, M. C., and Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height?. Med. Sci. Sports Exerc., 28: 1402-1412.

Brüggemann, G. P. (1983). Kinematics and kinetics of the backward somersault take-off from the floor. In proceedings of the 8th International Congress of Biomechanics (pp. 793-800). Nagoya, Japan.

Cheng, K. B., Wang, C. H., Chen, H. C., Wu, C. D., and Chiu, H. T. (2008). The mechanisms that enable arm motion to enhance vertical jump performance—A simulation study. J. Biomech., 41: 1847-1854.

Dapena, J. and Chung, C. S. (1988). Vertical and radial motions of the body during the take-off phase of high jumping. Med. Sci. Sports Exerc., 20: 290-302.

Dietz, V., Schmidtleicher, D., and Noth, J. (1979). Neuronal mechanisms of human locomotion. J. Neurophysiol., 42: 1212-1222.

Feltner, M. E., Bishop, E. J., and Perez, C. M. (2004). Segmental and kinetic contributions in vertical jumps performed with and without an arm swing. Res. Q. Exerc. Sport, 75: 216-230.

Feltner, M. E., Fraschetti, D. J., and Crisp, R. J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jumps. J. Sports Sci., 17: 449-466.
Fukushima, M., and Yamamoto, H. (1992). Biomechanics of teaching for hip pullover exercise in physical education class. In Proceedings of the 10th International Symposium on Biomechanics in Sports (p. 227). Milan, Italy.

Hara, M., Shibayama, A., Takeshita, D., and Fukashiro, S. (2006). The effect of arm swing on lower extremities in vertical jumping. J. Biomech., 39: 2503-2511.

Harman, E. A., Rosenstein, M. T., Frykman, P. N., and Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. Med. Sci. Sports Exerc., 22: 825-833.

Hill, A. V. (1922). The maximum work and mechanical efficiency of human muscles, and their most economical speed. J. Physiol., 56: 19-41.

Hwang, I., Seo, G., and Liu, Z. C. (1990). Takeoff mechanics of the double backward somersault. Int. J. Sport Biomech., 6: 177-186.

Jones, G. M. and Watt, D. G. D. (1971). Observations on the control of stepping and hopping movements in man. J. Physiol., 219: 709-727.

Kerwin, D. G., Webb, J., and Yeadon, M. R. (1998). Production of angular momentum in double backward somersaults. In proceedings of the 16th International Symposium on Biomechanics in Sports. Konstanz, Germany.

Konosu, A., Yoshioka, S., and Fukashiro, S. (2017). Upper limb joint torques during performances of kicking pullovers. Int. J. Sport Health Sci., 15: 137-144.

Konosu, A., Yoshioka, S., Yanagihara, D., and Fukashiro, S. (2020). Radial movements and lower limb joint kinematics during the takeoff phase of kicking pullovers. Int. J. Sport Health Sci., 18: 39-47.

Lees, A., Vanreentghem, J., and De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. J. Biomech., 37: 1929-1940.

Mathiyakom, W., McNitt-Gray, J. L., and Wilcox, R. (2006). Lower extremity control and dynamics during backward angular impulse generation in forward translating tasks. J. Biomech., 39: 990-1000.
Michitsuji, Y., Sato, H., and Yamakita, M. (2001). Giant swing via forward upward circling of the acrobat-robot. In Proceedings of the 2001 American Control Conference (pp. 3262-3267). San Francisco, USA.

Mohnsen, B. (2008). Teaching middle school physical education (3rd ed.) (pp. 379-394). Champaign: Human Kinetics.

Payne, A. H. and Barker, P. (1976). Comparison of the take-off forces in the flic flac and the back somersault in gymnastics. In proceedings of the 5th International Congress of Biomechanics (pp. 314-321). Jyväskylä, Finland.

Prassas, S., Kwon, Y. H., and Sands, W. A. (2006). Biomechanical research in artistic gymnastics: a review. Sports Biomech., 5: 261-291.

Shan, G. (2008). Kinematical characteristics of bicycle kick and side volley in soccer. In Proceedings of the 26th International Symposium on Biomechanics in Sports (p. 558). Seoul, Korea.

Shetty, A. B. and Etnyre, B. R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. J. Orthop. Sports Phys. Ther., 11: 198-201.

Stefanyshyn, D. J. and Nigg, B. M. (1998). Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps. J. Sports Sci., 16: 177-186.

Turoff, F. (1991). Artistic gymnastics (pp. 318-319). Dubuque: Wm. C. Brown Publishers.

Winter, D. A. (2009). Biomechanics and motor control of human movement (4th ed.) (pp. 82-138). New York: Wiley.

Yeadon, M. R. and Kerwin, D. G. (1999). Contributions of twisting techniques used in backward somersaults with one twist. J. Appl. Biomech., 15: 152-165.
Figure 1. Movement phase and analytical model. (a) The whole picture of kicking pullovers. The target phase of analyses were from the touchdown to takeoff of the support leg (takeoff phase). (b) Definition of the coordinate systems and joint angles. The angles of vectors including ground reaction force were shown as the elevation angle.
Figure 2. Ground reaction force (GRF) and moment around the center of mass (CoM). (a) Horizontal and vertical components of the GRF. (b) GRF magnitude. (c) The angle of the GRF (solid line) and the angle of the vector from the center of pressure (CoP) to the CoM of the whole body (dotted line). The definitions of the angles of the GRF and vector are shown in Figure 1b. (d) Moment around the CoM of the GRF. (e) Positional relationship between the CoM and the GRF vector. The x mark, the gray stick picture, and the black straight line are the CoM, support leg, and GRF, respectively. (a)-(e) were the means and standard deviations of the participants during the takeoff phase (Figure 1a).
Figure 3. Angular velocities and torques of the support leg joints. The means and standard deviations of the participants were shown for the takeoff phase (Figure 1a). The definition of joint angles are in Figure 1b.
Figure 4. Angular velocities and torques of the swing leg joints. The means and standard deviations of the participants were shown for the takeoff phase (Figure 1a). The definition of joint angles are in Figure 1b.
Figure 5. Kinematics of the center of mass (CoM) of the swing leg. (a) The solid line indicates the trajectory of the swing leg CoM (the collection of thigh, shank and foot) with the swing leg hip joint (asterisk) as the origin. The points on the solid line were plotted at equal time intervals.
The dashed line is a circular orbit centered on the hip joint passing through the position of the CoM at touchdown. The arrows are PASS (the Product of the relative Acceleration of the Swing leg CoM with respect to the swing leg hip joint and the Swing leg mass, Eq. [1]). (b) Relative velocity of the CoM with respect to the hip joint (upper) and PASS (lower). (c) Vertical component of PASS (solid line) and $PASST\text{an}$ (dotted line, Eq. [2]). For (a)-(c), the means and standard deviations of the participants were shown for the takeoff phase (Figure 1a).
Figure 6. Simulation of the relationship between the ground reaction force (GRF) angle and support leg joint torques to resist it. (a) The torques that each joints of the support leg have to exert against the 1N GRF calculated by Eq. (3). Positive and negative values indicate flexion and extension torques, respectively. (b) The curved surface of mesh is the torque that hip joint has to exert against the GRF with the time of the takeoff phase and the angle of the GRF as parameters (Eq. [4]). The solid line is the participant’s average of the measured GRF angle at each normalized time (Figure 1a).
Name
Akira Konosu

Affiliation
Department of Life Sciences, Graduate School of Arts and Sciences, The University of Tokyo, Japan

Address
3-8-1, Komaba, Meguro-ku, Tokyo, 153-8902 Japan

Brief Biographical History
2018 Doctor of Arts and Sciences, The University of Tokyo
2018-Present: Research Associate, Graduate School of Arts and Sciences, The University of Tokyo

Main works
Konosu, A., Yoshioka, S., and Fukashiro, S. (2017). Upper limb joint torques during performances of kicking pullovers. Int. J. Sport Health Sci., 15: 137-144.
Konosu, A., Yoshioka, S., Yanagihara, D., and Fukashiro, S. (2020). Radial movements and lower limb joint kinematics during the takeoff phase of kicking pullovers. Int. J. Sport Health Sci., 18: 39-47.
Konosu, A., Ikeda, N., Yoshioka, S., Yanagihara, D., and Fukashiro, S. (2021). Biomechanical differences between successful and unsuccessful kicking pullovers by 10-year-old children. Int. J. Sport Health Sci., 19: 1-9.

Membership in Learned Societies
Japan Society of Physical Education, Health and Sports Sciences
1  Japanese Society of Biomechanics
2  Tokyo Society of Physical Education, Health and Sports Science
3