In this study, we determined upper limb joint torques during performances of kicking pullovers. Kinematics and bar reaction forces (BRFs) were measured during successful kicking pullovers by 10 healthy adult males, with the horizontal bar set at 75% to the individual subject's heights. Sagittal plane analyses using an 11-segment link model were performed between the period from takeoff to the upside-down position. Large extension torques of elbows and shoulders of both arms were observed (1.01 ± 0.14 and 2.08 ± 0.30 Nm/kg as the sum of bilateral arms, respectively) and accompanied by large vertical BRF (0.71 ± 0.07 BW). Because the angular momentum about the center of mass (CM) was mostly satisfied at takeoff, large horizontal BRF after takeoff may be avoided. However, vertical velocity of the CM at takeoff (1.1 ± 0.1 m/s) was insufficient to raise by the necessary distance against gravity, and compensation by vertical BRF after takeoff was demonstrated. Moreover, vertical BRF was responsible for maintaining the position of the body at around the target height against gravity during the second half of the target period. These observations suggest that successful kicking pullovers require large elbow and shoulder extensor strengths, and strengthening of these muscles is effective for achieving kicking pullovers.

Keywords: kicking pullover, gymnastics, upper limb joint torques, vertical velocity, strength

1. Introduction

Pullover (or upward circle) is one of the most fundamental and introductory skills in gymnastics (Turoff, 1991), and allows performers to safely mount a horizontal bar with backward rotation at the start of performances. Practicing pullover facilitates the development of many essential elements for gymnasts, including strength, rotation awareness, gripping technique, and maintenance of support position (American Sports Education Program and USA Gymnastics, 2009). Achieving pullover, namely, making a mount without assistance, gives great confidence to beginners (Goldmann, 2014), and is central to physical education curriculums of elementary and middle schools (Delač et al., 2007; Fukushima and Yamamoto, 1992; Mohnsen, 2008). Thus, techniques for achieving pullover have been investigated by gymnasts and are of interest to general students and their teachers.

Delač et al. (2007) focused on five representative training skills for gymnastics, including cartwheel, handstand, squat vault, pirouette, and pullover, and identified morphological and strength factors that affect the performances of these skills. In their study, the success and execution of pullover were negatively affected by obesity and were positively affected by motor abilities that are associated with leg and arm strengths. These associations suggest that sufficient strength to accelerate the body upward against gravity is essential for the performance of pullovers.

Biomechanical studies of joint torques during typical successful pullovers are required to determine the strength requirements. Fukushima and Yamamoto (1992) have reported biomechanical parameters of pullover and evaluated their education method for pullovers by recording EMG, kinematics, and kinetics on elementary school students. Improvements in pullover were found to involve changes in parameters such as vertical ground reaction force, vertical force applied to the bar, and the activities of latissimus dorsi and rectus abdominis muscles. However, parameters that represent
magnitudes of strength exerted on specific joints were not determined. Moreover, because these parameters were not investigated throughout the movement, little is known of the mechanisms by which strengths are required for pullover.

To perform a successful pullover, gymnasts have to raise their body against gravity and rotate backward. These movements require the application of certain external forces from a horizontal bar and exertion of joint torques to resist these forces. Upper limb joints would require particularly large torques because the shoulder joint exerts a considerably larger torque than the hip joint during kips, which is a fundamental mount on a horizontal bar, similar to pullovers (Yamasaki et al., 2010).

Pullover is classified into various patterns according to whether it is started with a suspended posture or a takeoff from the ground, and according to styles of takeoff. The most introductory pattern requires takeoff by pushing off the ground with one leg and swinging the other leg up (Tuorro, 1991), and is known as the “kicking pullover.”

Vertical velocity of the center of mass (CM) and angular momentum about the CM at takeoff are prepared before takeoff during kicking pullovers, and allow performers to achieve a pullover with smaller reaction forces from the bar and less upper limb strength. This contribution of takeoff kinematics may be significant, because it involves contributions of ground reaction forces before takeoff which are generated by strong lower limbs.

The purpose of this study was to determine upper limb joint torques during successful kicking pullovers. The target period was from takeoff to the upside-down position, during which the success or failure of kicking pullovers is determined.

2. Methods

2.1. Participants

Ten healthy males who can successfully perform kicking pullover (age, 25.2±2.1 years; height, 1.71±0.04 m; body mass, 62.8±5.5 kg) participated in the study. All participants had acquired their skills in elementary school classes, although none had majored in gymnastics. All participants provided informed written consent and the experimental procedure was approved by the research ethics committee of the university.

2.2. Protocol

The experiment was performed with an apparatus of our own construction (Figure 1). The horizontal bar was made of iron and the radius was 14 mm. Before the experiment, participants were asked to choose bar heights that were most conducive to successful kicking pullover, and all participants chose bar heights that fell between the chest and shoulder. Therefore, to control the experimental condition, the bar was set at 75% of each individual’s height, corresponding with the upper part of the chest. After warming up with several trials of kicking pullovers, participants were instructed to perform five kicking pullovers with overgrip at their own pace. Postures of lower limbs were not specified and all participants achieved successful pullovers in all five trials.

2.3. Data collection

Positions of anatomical landmarks, bar reaction forces (BRFs), and ground reaction forces (GRFs) were measured throughout the motion. A 13-camera motion capture system (Motion Analysis Corp., CA, USA) was used at 200 Hz to record positions of 24 and 4 reflective markers that were placed on anatomical landmarks and the bar, respectively. The data were then smoothed using a zero-lag, 4th order, Butterworth low-path filter with cut-off frequencies of 8.3–14 Hz, which were determined using...
residual analyses (Winter, 2009). A force plate (9281B, Kistler, Winterthur, Switzerland) was used at 2000 Hz to measure GRF that were applied to the support leg foot.

2.4. Measurements of bar reaction forces

To determine vertical and horizontal BRFs, the bar was equipped with a sensory system that detected distortions of the bar. First, a total of eight strain gauges (G1–G8) (N11-FA-10-1000-11-VSE1, Showa Measuring Instruments Co., Ltd., Tokyo, Japan) were attached to both ends of the bar inside the column supports (Figure 1). Second, a gauge circuit for measuring vertical BRF (CV) was formed using four of those gauges attached to top and bottom faces of the bar (G1–G4) and an amplifier (CDV-900A, Kyowa Electric Instruments Co., Ltd., Tokyo, Japan) (Figure 2a). Vertical forces that were applied at the middle of the bar were linearly dependent on the output potential of CV recorded at 2000 Hz with a correlation coefficient (r) of –0.9998. Differences in output were less than 1% between positions of the bar to which vertical forces were applied. Finally, another gauge circuit for measuring horizontal BRF (CH) was formed using the other four gauges attached to side faces of the bar (G5–G8). Horizontal forces applied at the middle of the bar were linearly dependent on the output potential of CH with a correlation coefficient (r) of –0.9999.

Interferences on CV outputs due to horizontal forces were approximately 0.4% of the CV outputs from vertical forces of the same magnitude. Therefore, vertical BRF was calculated independently of CH output as the sum of forces applied on both hands. Specifically, measured CV output was divided by the inclination of the regression line applied to the force–output scatter plot (Figure 2d). Horizontal BRF was calculated using the same method.

2.5. Analysis

Kinematics and kinetics were calculated using sagittal plane analyses with an 11-segment rigid body link model composed of the head, trunk, hand, forearm, upper arm, bilateral thighs, bilateral legs, and bilateral foots segments. Inertia parameters of these segments were calculated using the regression equation described by Winter (2009). The origin of the coordinate system was the center of the bar, and the horizontal axis was taken with the direction of approach as positive (Figure 3). Parameters related to rotation were reported with backward rotation as positive. Upper limb joint torques (internal torques) as the sum of the bilateral arms were calculated using BRF data with inverse dynamics (Winter, 2009). To model the wrist, elbow, and shoulder, positions of the ulnar styloid process, epicondyle of the humerus, and the acromion were averaged between bilateral arms, respectively (Figure 3). The force points of BRFs were as-
Figure 3  Coordinate system and the target period. The center of the horizontal bar was the origin of the coordinate system. An example of movement is shown.

Assumed to be located at the center of the bar, frictional moment about the center of the bar (Sheets and Hubbard, 2009) being neglected. The whole body angular momentum about the CM was calculated using the linear and angular velocities of the segments (Robertson et al., 2013).

2.6. Target period

The target period of analysis was from takeoff to the time when the abdomen makes contact with the bar, during which external forces, apart from gravity, are only those between the hands and the bar (Figure 3). The takeoff was identified as the timing at which vertical GRF fell below 10 N. The contact with the bar was identified with rapid change in BRF. Specifically, the timings at which secondary derivatives of horizontal BRF show maximal values were taken.

3. Results

3.1. Joint torques

Joint torques of the wrist, elbow, and shoulder as the sum of bilateral arms are shown in Figure 4a. Wrists exerted flexion torque, with the peak value $0.40 \pm 0.09$ Nm/kg as sum of bilateral arms. Elbows exerted extension torque during the first half of the target period and exerted flexion torque during the second half of the target period. The peak extension torque was $1.01 \pm 0.14$ Nm/kg, and flexion torque continued to increase until the abdomen made contact with the bar; reaching $0.84 \pm 0.44$ Nm/kg. The peak extension torque of the shoulders was $2.08 \pm 0.30$ Nm/kg.

3.2. Bar reaction forces

BRF data are shown in Figure 5a. The mean vertical BRF over the target period ($0.71 \pm 0.07$ BW) was much larger than the mean horizontal BRF ($-0.10 \pm 0.10$ BW).

3.3. Vertical movements

Vertical movements of the CM are shown in Figure 6. In these experiments, the CM rose by $20.3 \pm 5.5$ cm through the target period, reflecting the necessary elevation of CM for successful kicking pullover under the present bar height conditions. However, the vertical velocity of CM at takeoff was $1.1 \pm 0.1$ m/s, which was calculated to enable a CM rise of only $6.4 \pm 1.3$ cm against gravity. At the 50% normalized time, rises in the CM had progressed to $82 \pm 26\%$ of the entire target period.

3.4. Backward rotation

As shown in Figure 6, the whole body angular momentum about the CM peaked immediately after takeoff. The angular momentum at takeoff accounted for $95 \pm 4\%$ of the peak value. That is, backward rotation was achieved by preventing reductions of the angular momentum prepared before takeoff.

3.5. Ground reaction forces in takeoff phase

Figure 5b shows the GRF applied to the support leg foot in the takeoff phase. The peak values of the horizontal and vertical components were $-0.88 \pm 0.25$ and $2.60 \pm 0.39$ BW, respectively.
4. Discussion

The purpose of this study was to investigate the upper limb joint torques during kicking pullovers. Joint torques of the wrist, elbow, and shoulder were determined, and were accompanied by a large vertical BRF. Although vertical velocity at takeoff was insufficient to the required CM rise, the major part of rise in CM was accomplished in the first half of the target period (Figure 6), indicating vertical BRF in the period compensated for the insufficiencies. During the second half of the target period, rises in CM progressed by only about 18%, whereas backward rotation continued to progress at the same rate as in the first half of the target period (Figure 6). Vertical BRF was kept close to the body weight (Figure 5a). These results suggest that about half of the backward rotation required for the target period had been left uncompleted by the first half period, and vertical BRF in the second half period was responsible for maintaining the vertical position of the CM at around the target height, during which the rotation was completed.

Horizontal BRF was smaller than vertical BRF. Since vertical distance from the CM to the bar was larger than the horizontal distance through the target period (Figure 3), the horizontal BRF was efficient to increase the angular momentum about the CM, whereas the vertical BRF had little effect on the angular momentum. However, the angular momentum was close to the peak value at takeoff (Figure 6), suggesting that sufficient angular mo-
Figure 6  Vertical movements of the center of mass (left side) and rotation (right side). Rotation angles were formed between the vector direction from the shoulder to the center of mass and the horizontal axis. Ensemble averages and standard deviations are presented. The coordinate system is shown in Figure 3.

momentum had been obtained at takeoff and dispensed with large horizontal BRF after takeoff.

In the present study, we did not include the frictional moment applied by the bar in our calculations of upper limb joint torques, and this measurement would validate our data. However, we estimated the frictional moment by subtracting the moment of the body weight about the bar from the time differentiated angular momentum of the body about the bar. Hence, according to the definitions described in a previous study, the coefficient of the frictional moment was around 0.48; further, this value is in loose agreement with the experimentally determined value of 0.85 (Sheets and Hubbard, 2009) and was, therefore, used with BRF data to calculate frictional moments at each time point in the target period (Figure 4b). However, in calculations of elbow and shoulder extension torques, exclusion of frictional moments led to 1.9% and 1.2% overestimations of peak values, indicating that frictional moments contribute little to upper limb joint torques.

Peak upper limb joint torques were determined using previously reported maximum isometric voluntary torques of wrists, elbows, and shoulders (Askew et al., 1987; Holzbaur et al., 2007; Mayer et al., 1994). Peak wrist flexion torques in the present study were 66±15%, peak elbow extension were 79±11%, maximum elbow flexion torques were 53±28%, and peak shoulder extension torques were 86±12%. These data suggest that successful kicking pullovers require large elbow and shoulder extensor strengths that are comparable to maximum voluntary strengths. Moreover, as moderately low bar of 75% to the subject’s heights were used in this study, higher bar will require larger strengths for larger CM rises. Hence, strengthening the elbow and shoulder extensor muscles would be effective to achieve kicking pullovers for individuals who have relatively small strengths. To further investigate the minimum required strengths, future work should sample sufficient number of successful and unsuccessful movements.

The vertical velocities at takeoff were considerably small compared with the vertical jumps by adult males and backward somersaults by beginner gymnasts (Baechle and Earle, 2000; Burgess and Noffal, 2001). However, the influence of changes in the vertical velocity on the necessary upper limb joint torques for successful kicking pullovers suggests that the velocities in this study were moderate to reduce the torques. Although increased vertical velocity
may contribute to decreases in vertical BRF and peak elbow extension torques during the early stages of the target period, this velocity would also advance the timing of peak heights of the CM (Figure 6). As a consequence, the period during which the vertical BRF has to maintain the position of the CM to the target height against gravity would start earlier (Figure 5a), and vertical BRF and the peak shoulder extension torque at the middle-stage (Figure 4a) would increase. In contrast, too little vertical velocity would increase the requirement of vertical BRF after takeoff, leading to increased peak or maximum torques of the elbow and shoulder. Taken together, these data suggest that moderate vertical velocity at takeoff minimizes the necessary upper limb joint torques, and that skilled performers master the resulting balance between joints.

In this study, adults were selected as subjects to minimize individual differences in the neuromuscular development. However, information for supporting junior gymnasts and students is important, because many of them learn the kicking pullover. The qualitative parameters of the result, including the direction and general timings of peak torques, can apply to children. However, the magnitudes of the required strengths are beyond the scope of application, because these magnitudes depend on many factors based on the necessary rise in CM and body sizes, and the dependences are currently uncertain. The effects of development and technique improvements on the required strengths are under review.

During kicking pullovers, one leg pushes off the ground and the other swings up in the takeoff phase; however, these legs couple toward the support position (Figure 3). This observation suggests that angular momentum arises within the horizontal and frontal planes and is regulated in the target period, which may require uneven BRFs and joint torques between both arms. Specifically, the arm on the side of the support leg likely exerts larger torques to resist the BRFs that are required to pull up the support leg and to suppress the angular momentum of the swing-up leg. However, the present study could not separate the torques of both arms because of the sensory system construction. Further insights into this three-dimensional movement and the differences in the roles of both arms are warranted.

The CM had a horizontal velocity of approximately 1.3 m/s at touchdown but had little horizontal velocity of approximately 0.3 m/s at takeoff (Figure 3). In the takeoff phase, the horizontal component of the GRF was directed backward and the vertical component amounted to approximately 2.6 BW (Figure 5b). These results suggest that the horizontal velocity of the approach was utilized for producing vertical velocity and angular momentum in the takeoff phase, and these takeoff mechanisms have aspects that are common to those of running jumps. An energetics approach will be effective to further investigate the techniques for obtaining the takeoff kinematics of kicking pullover (J. Stefanyshyn and Nigg, 1998).

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