How Could Runners Rotate Their Bodies about the Vertical Axis so that the Whole-body Orientation Could Be Maintained along a Curved Path?

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The purpose of the present study was to determine how runners sprinting along a curved path could rotate their whole body about the vertical axis to maintain their stance so that they continually faced the ever-changing running direction. Ten healthy men were asked to run at 5 m/s along a straight path (RS) and a curved path with a 5-m radius (RC). The running direction during RC was counterclockwise as viewed from above (CCW). A motion capture system (240 Hz) was used to record the three-dimensional coordinates of the reflective markers attached to each subject. The changing patterns of the angular momentum of each segment and the average angular momentum of the whole body in each contact and flight phase were compared between the two movements. In all the phases, the average angular momentum during RC was significantly directed more toward the CCW direction than that during RS. In contrast, the angular momentum of the head and trunk during RS changed periodically from positive to negative values, while that during RC continued to exhibit positive values throughout the stride cycle. The changing pattern of the angular momentum of the left leg during RC was in the phase opposite to that during RS because the subjects swung the left leg on their right side. The left leg moved in an elliptical trajectory in a direction opposite to the rotation of the whole body on the horizontal plane during RC; this presumably generated reactional rotation effects on the other segments to maintain stance that allowed the subject to keep facing the running direction.

Keywords: whole body movement, angular momentum, turning effect, action-reaction

1. Introduction

In field- or court-based sports, athletes change their movement direction in response to the dynamic game situation. A soccer player changes the movement direction for an average 727 times per game (Bloomfield et al., 2007). In other studies on field hockey games, sprinting with change in the movement direction was about two times of that while sprinting along a straight path (Spencer et al., 2004; Spencer et al., 2005). These previous studies indicated a high frequency of sprinting with change in the movement direction in such sports. Moreover, elite players of soccer and field hockey have a superior ability to sprint while changing the movement direction compared to non-elite players (Keogh et al., 2003; Reilly et al., 2000). Therefore, improvement in the ability to sprint while changing the movement direction may increase the competitive performance in field- or court-based sports.

Based on the Bloomfield movement classification established to categorize various movements observed in field- or court-based sports (Bloomfield et al., 2004), sprinting while changing the movement direction is classified into the following three types: 1) swerve, 2) turn, and 3) running on a curved path. Turn and swerve refer to rapid changing of the movement direction during one foot contact phase and have often been studied in biomechanical trials where they have been referred using other terms, such as “cutting maneuver,” “sidestep,” and “change of direction.” In contrast, few previous
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studies have assessed running on a curved path, with most of them having analyzed sprinting on a curved section of an official running track. Therefore, the mechanism involved in whole-body movement while running on a curved path with a small radius, frequently observed in field- or court-based sports remains unclear.

The whole-body movement consists of a curvilinear translation of the whole-body center of mass (CM) and a rotation of each body segment about the whole-body CM. Based on this model, the mechanism of the whole-body movement during “turning” has been analyzed from the following two viewpoints: “deflection,” a change of movement direction of the whole-body CM on a horizontal plane, and “rotation,” a change in the orientation of the whole-body about the vertical axis passing through the whole-body CM (Jindrich and full, 1999; Jindrich et al., 2006; Patla et al., 1991). Running on a curved path also involves these two aspects of whole-body movement; thus, the analytical model constructed from “deflection” and “rotation” can be adapted for the mechanism of whole-body movement during running on a curved path.

In a previous study focusing on “deflection” during sprinting on a curved section of an official running track (path radius: 31.5 m), an impulse of a normal component of a horizontal ground reaction force (GRF) was larger in the inside foot contact phase than in the outside foot contact phase (Hamill et al., 1987). In contrast, the impulse of the tangential component of the horizontal GRF did not differ between these two phases. These results suggested that the inside leg played a greater role in “deflection” than the outside leg. However, another study reported contradictory results regarding running on a curved path with a 5-m radius in a counterclockwise direction as viewed from above (CCW direction) (Smith et al., 2006). One possible explanation for this conflicting finding could be the continuous change in the contribution ratio of the inside leg to that of the outside leg, depending on the path radius. In support of this possibility, continuous changes were found in the peak GRF and foot contact time during running on a curved path with radii ranging from 1-6 m (Chang and Kram, 2007). These results indicate that the mechanism of “deflection” varies, depending on the path radius. Meanwhile, the mechanism of “rotation” while running on a curved path was analyzed on the basis of angular kinetics (Azuma and Yanai, 2012). This study demonstrated that experienced sprinters running with the maximum effort on a curved section of an official running track possessed a forward somersaulting angular momentum throughout the stride cycles while the runner’s body rotated CCW as viewed from above to keep facing the ever-changing running direction. This complex angular motion requires the vector representation of the forward somersaulting angular momentum to change its direction in the CCW direction relative to an inertial reference frame. They found that this change in the direction of forward somersaulting angular momentum vector occurred during the outside foot contact phase. The GRF that generated these change in the angular momentum differed according to the path radius (Chang and Kram, 2007); therefore, the mechanisms of “rotation” may also vary, depending on the path radius. However, to our knowledge, no study has assessed the mechanism of “rotation” while running on a curved path with a small radius, frequently observed in field- or court-based sports. Therefore, we aimed to determine how runners sprinting on a curved path with a small radius could rotate their whole-body about the vertical axis passing through the whole-body COM to maintain a stance that allowed them to keep facing the ever-changing running direction.

2. Methods

2.1. Subjects

Ten healthy men (Height: 1.73 ± 0.05 m, Mass: 67.2 ± 7.0 kg, Age: 25.9 ± 1.8 years) who exercised more than once a week voluntarily participated in the present study. The right foot was more dominant in all the subjects, based on their ball-kicking practice. Informed consent was obtained from all the subjects prior to study initiation. The experimental protocol was approved by the Ethics Committee of Human Research of the Waseda University.

2.2. Experimental setup

An experimental running path was set on a wooden floor in the gymnasium. Two force plates (FP6012-15 Bertec corp.) sampling at 2400 Hz were embedded to measure each GRF in two adjacent
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Figure 1 Overhead view of the experimental setup.

foot contact phases. A motion capture system (Eagle, Motion Analysis corp.) was used to record the three-dimensional coordinates of the reflective markers (Figure 1). Three-dimensional residuals of the motion capture system were <0.5 mm throughout data collection for all the subjects. A fifteen segment model was used to analyze the subject's movement (Ae et al., 1992). Three or four reflective markers were attached on each segment to calculate the orientation and segmental CM of each segment during the experimental trials. Locations of the attached markers were the upper side of the right and left heel, the lower side of the right and left heel, the lateral side of the right and left heel, the lateral side of the right and left shank (rigid plate with four markers), the lateral side of the right and left thigh (rigid plate with three markers), the right and left ASIS, the midpoint between the right and left PSIS, the lower end of rib on the right and left side, the sternal notch, the right and left acromion, the seventh cervical vertebra, the lateral epicondyle of the right and left humerus, the medial epicondyle of the right and left femur, the right and left greater trochanter, the right and left tragus, and the vertex. These additional markers were replaced before the experimental trials. Both ends of the longitudinal axis of each segment during the static trial were defined as the joint centers linking the adjacent segments. Ends of the axis without the adjacent segment in each foot, each hand, and head segment were defined as the toe, the midpoint between the second and fifth MP joint, and the vertex, respectively. A singular value decomposition method (Söderkvist and Wedin, 1993) was utilized to optimally determine the ends of the longitudinal axis of each foot, each shank, each thigh, and head during the experimental trials because the markers that were required to calculate the longitudinal axis of these segments were replaced before the experimental trials.

2.3. Experimental trials

All the subjects wore the same model of indoor sport shoes fitting as per their foot size. They performed warm up exercises and practiced the experimental movements as many times as they desired. The experimental movements consisted of running along a straight path (RS) and a curved path with 5-m radius (RC). The subjects performed each movement six times in a randomized order. In the three trials including six repetitions of each movement, they took a first and second step on the force plates using their right and left foot, respectively. In the other three trials of each movement, the opposite foot was used for each step. The capture volume was set to include a range from a flight phase before the first step to a flight phase after the second step. For the RS trial, the subjects were asked to run along the straight path as usual and continue running at a constant speed of 5 m/s in the capture volume. For the RC trial, they were asked to run along the curved path in the CCW direction while remaining on the path with a constant speed of 5 m/s in the capture volume. Distances of the running paths from the start position of each trial to the capture volume were set to > 15 m so that the subjects accelerated enough to maintain a constant running speed in the capture volume. Two photocells (E3G-MR19T, Omron Corp.) were used to monitor the running time in a 2-m distance in the capture volume. If an average running speed calcu-
lated from the running time exceeded 5 m/s ± 0.25 m/s or the entire sole of the foot did not fall in each force plate during the first and second steps, the trial was repeated.

2.4. Data processing

MATLAB (R2010a, Math Works) was used to process the kinematic and kinetic data. The three-dimensional coordinates of the reflective markers were smoothed by a fourth-order Butterworth low pass filter. The cut-off frequency was set at 12 Hz based on a previous study that used the same experimental set up (Sanna and O’Connor, 2008). The GRF data was downsampled to 240 Hz by averaging every 10 samples. Whole-body CM and segmental CM of each segment was calculated using the kinematic data. The data analyses were performed for a section starting from a frame in which the whole-body CM reached the highest position in a flight phase before the first step to a frame in which the whole-body CM reached the highest position in a flight phase after the second step. A foot contact phase of each step was defined as the period in which the vertical component of the GRF exceeded 20N; these were termed right-foot contact phase (RCP) and left-foot contact phase (LCP). The flight phase immediately after RCP was termed the right-foot flight phase (RFP), and another flight phase in a stride cycle was termed the left-foot flight phase (LFP). The data analysis section was comprised of three flight phases and two contact phases. Please note that the first and last flight phases were same in the adjacent stride cycles and, thus, we assumed these two as the same phase. A moving coordinate system (AP-ML-vertical) fixed on the whole-body CM was defined in each frame. The AP axis was calculated as a unit vector of the average horizontal velocity of the whole-body CM during each flight phase and that of an instantaneous velocity of the whole-body CM during each contact phase. The ML axis was a unit vector of a cross product of the vertical axis and the AP axis.

2.5. Parameters

2.5.1. Change in the running speed

The change in the running speed of each step was calculated as a change in the magnitude of the average horizontal velocity of the whole-body CM between the flight phase before and after each contact phase.

2.5.2. Inclination angle of the movement plane

Leg swing movements while running on a straight path occur on the sagittal planes parallel to both the AP and vertical axes, while the planes on which the leg swing movements occur while running on a curved path incline to a center of the path curvature. In the present study, the inclination of the plane of each leg movement was used to estimate the whole-body inclination during each running movement. The leg CM was calculated as CM of a system constructed from the foot, shank, and thigh segment. Principal component analysis was conducted to determine the best fitting plane of three-dimensional coordinates of the leg CM throughout the stride cycle in the moving coordinate system. Plane inclination was determined as a projection angle formed by the normal vector of the fitting plane and the ML axis on the ML-vertical plane. An inclination angle of the movement plane was defined as the average of the angles calculated for each leg. The negative angle indicated the inclination of the whole body to a center of path curvature.

2.5.3. Average angular momentum in each phase

The angular momentum of the whole body about the whole-body CM was determined for one complete stride cycle using the method described by Dapena (1978). The vertical component of the angular momentum was normalized by the squared body height and the body mass, as in previous studies (Azuma and Yanai, 2012; Dapena, 1978; Hinrichs, 1987). Average angular momentum was defined as an average of the normalized value in each phase and was described by the units s⁻¹ with 10⁻³. A positive value indicated angular momentum in the CCW direction.

2.5.4. Changing pattern of the categorized angular momentum

The angular momentum of each body segment was categorized into the head and trunk, the right arm, the left arm, the right leg, the left leg, both arms, and both legs. One complete stride cycle was normalized to 100 time frames. The categorized angular momentum at each normalized time frame was calculated with third-order spline interpolation.
2.6. Statistical analyses

Averages were calculated for all the parameters of each subject for the six trials. Two-way repeated-measures analysis of variance (ANOVA) was conducted for the change in the running speed with the two movements and the two-foot contact phases. In addition, these four average values were compared with zero using four separate one-sample t-tests. The inclination angles of the movement plane were compared between the two movements using paired t-test. Two-way repeated measures ANOVA was conducted for the average angular momentum with the two movements and the four phases. The average changing patterns of each categorized angular momentum and the whole-body angular momentum were compared between the two movements.

3. Results

There were no interactions or main effects in the two-way ANOVA for the change in the running speed. No difference was found in the four separate one-sample t-tests for the average values. The inclination angle of movement plane was significantly higher during RS \((-0.7^\circ \pm 1.5^\circ)\) than that during RC \((-38.3^\circ \pm 4.8^\circ)\). The average angular momentum during RS showed a cyclic change form positive to negative \((RFP: 3.6 \times 10^{-3} \pm 2.0 \times 10^{-3} \text{ s}^{-1}, \ LCP: 3.5 \times 10^{-3} \pm 1.3 \times 10^{-3} \text{ s}^{-1}, \ LFP: -3.2 \times 10^{-3} \pm 1.7 \times 10^{-3} \text{ s}^{-1}, \ RCP: -2.7 \times 10^{-3} \pm 1.3 \times 10^{-3} \text{ s}^{-1})\). In contrast, that during RC was positive in all phases \((RFP: 7.2 \times 10^{-3} \pm 3.0 \times 10^{-3} \text{ s}^{-1}, \ LCP: 8.6 \times 10^{-3} \pm 2.9 \times 10^{-3} \text{ s}^{-1}, \ LFP: 0.8 \times 10^{-3} \pm 3.0 \times 10^{-3} \text{ s}^{-1}, \ RCP: 0.2 \times 10^{-3} \pm 4.0 \times 10^{-3} \text{ s}^{-1})\). In the two-way ANOVA, the main effects of the movement and the phase were significant \((p<0.001)\), while no interaction was found (Figure 2). Each angular momentum was categorized into five parts, as shown in the upper side of Figure 3. The angular momenta of the right and left arms during RS changed periodically in the same phase. The angular momenta of the right and left legs during RS showed the changing pattern in the phase opposite to that during RS. Thus, the changing patterns of the angular momenta of the right and left legs during RC were opposite to each other. The angular momentum of the head and trunk during RS changed periodically from positive to negative, while that during RC remained positive throughout the stride cycle. Each angular momentum was categorized into three parts, and the whole-body angular momentum is shown on the lower side of Figure 3. The whole-body angular momentum during both movements changed periodically in the same phase, while its sequential line of RC was located above that of RS. During both movements, the angular momentum of both arms changed periodically in the phase opposite to that of both the legs. The changing patterns of the angular momentum of both arms and both legs during RC were similar to those during RS.

4. Discussion

In the present study, the angular aspects of the whole-body movement were compared between RC and RS to determine how runners sprinting on a curved path could rotate their whole-body to maintain a stance that allowed them to keep facing the ever-changing running direction. Similar changing patterns were found in the angular momenta of the right and left arms about the vertical axis passing through the whole-body CM during RC and RS. In contrast, while the changing patterns of the angular momenta of the right and left legs during RS were in the same phase, those during RC were opposite
Figure 3  Average changing patterns of the categorized angular momentum.

to each other. During both movements, the angular momentum of both the arms changed periodically in the opposite phase to that of both legs. The angular momentum of the head and trunk during RS changed periodically from positive to negative values, while that during RC maintained positive values throughout the stride cycle. The angular momentum in the CCW direction maintained throughout the stride cycle was caused by these distinctive changing patterns of the angular momentum of each segment during RC that enabled the achievement of whole-body rotation to maintain a stance that allowed the runner to keep facing the ever-changing running direction.

During both movements, the running speed did not change over multiple steps. These results suggest that the subjects kept their running speed constant in each trial. Average values of the inclination angle of the movement plane were about 0° during RS and 40° during RS, indicating great inclination of the subject’s whole body to the center of path curvature during RS.

The angular momentum during RS showed peak values and changing patterns similar to that reported in a previous study that focused on the same movement (Hinrichs, 1987). This previous study demonstrated that athletes running on a straight path possessed the angular momentum of the whole body about the whole-body CM throughout the stride cycle, while their whole-body configuration was the same at the beginning and end of a stride cycle. The angular momentum in the present study was determined by the same method as that used in this previous study. Therefore, all the calculations regarding angular momentum in the present study can be considered valid.

The whole-body angular momentum during RC was directed more toward the CCW direction than
that during RS, showing positive values almost throughout the stride cycle. The angular momentum of both the legs during RC showed a changing pattern similar to that during RS because a part of the great angular momentum of the right leg was canceled out by that of the left leg in the opposite phase during RC. Throughout the stride cycle while RS, the magnitude of the angular momentum of both the legs was much larger than that of both the arms in the opposite phase; that of the head and trunk was almost zero. Thus, the angular momentum of the whole body during RS changed periodically from positive to negative values in the same phase as that of both the legs. In contrast, the angular momentum of the whole body during RC was in the CCW direction almost throughout the stride cycle. This distinctive changing pattern during RC was caused by the following two mechanisms: 1) the magnitude of the angular momentum of both the legs was not much larger than that of both the arms in the opposite phase, 2) the angular momentum of the head and trunk in the CCW direction was maintained throughout the stride cycle. These results suggest that the angular momentum of the whole body in the CCW direction caused by the movement of the head, trunk, and each leg was maintained throughout the running cycle, achieving the rotation of the whole body to maintain a stance that enabled the runner to keep facing the running direction while running on a curved path with a small radius. The angular momentum of whole body in the CCW direction was maintained almost throughout the stride cycle; this conflicts with previous reports on sprinting on a curved section of an official running track (Azuma and Yanai, 2012). In this previous study, the runner sprinting on a curved path possessed whole-body angular momentum in the CW direction, while they rotated their whole-body in the CCW direction throughout the stride cycle. The key reason for this interesting result was found to be the projection of the angular momentum of both the legs on the vertical axis. Athletes running on a straight path possess considerable angular momentum in a forward somersault direction caused by the swing movement of both the legs (Hinrichs, 1987). When a runner sprinting along a curved path inclines the whole body to a center of path curvature, great angular momentum of both the legs is projected on the vertical axis as the component in the CW direction. Thus, the mechanism responsible for the result was that the projection of the angular momentum of both the legs was larger than the angular momentum of the other segments that were required to maintain a stance that allowed the runner to keep facing the ever-changing running direction. In the present study, the angular momentum of both the legs in the forward somersault direction during RC may be smaller than that in this previous study because the subjects could not sprint along the curved path with 5-m radius at a speed as high as that while sprinting on a curved section of an official running track (radius: 39.15 m). Therefore, the subject's whole-body inclined about 40° although the projection of the angular momentum of both the legs in the CW direction was smaller than the angular momentum of the other segments in the CCW direction during RC. These contradictory results about the angular momentum of the whole body about the vertical axis passing through the whole-body CM indicate the difference in the cyclic movements of both the legs between sprinting on a curved path with a small radius and that on a curved section of a track.

To compare the cyclic movements of both the legs between RC and RS, an inclined coordinate system (AP-ML-V′) was defined as the moving coordinate system with a tilt at the inclined angle of the movement plane. Figure 4 shows the ML′ component of the angular momentum of each leg and their sum. As in the previous study that focused on running on a straight path (Hinrichs, 1987), the angular momentum of a leg swinging backward was larger than that of the other leg, and their sum was in the forward somersault direction almost throughout the running cycle during RS. In contrast, the sum of the angular momentum of each leg during RC was in the backward somersault direction in a few phases because the angular momentum of a leg swinging backward was smaller than that of the other leg. The majority part of the angular momentum of each leg is accounted for by the moment of linear momentum of each leg about the whole-body CM (Hinrichs, 1987). Based on this observation, the changing patterns of the ML′ component of the angular momentum of each leg during RC indicates that the velocity and/or the moment arm of the segmental CM of each leg relative to the whole-body CM differed bilaterally. These two parameters were additionally calculated as the magnitude of the velocity of the leg CM relative to the whole-body...
CM and the distance between the leg CM and the whole-body CM, respectively. The average values in the stride cycle were compared between the right and left leg. The relative velocity of the left leg was significantly larger than that of the right leg during RC, while no other bilateral difference was found in the additional comparison. The bilateral difference in the relative velocity during RC indicated that the subjects swung their right leg on the outside about a step width relative to the left leg, and the length of the trajectory of the right leg CM was longer than that of the left leg. These bilateral characteristics suggest that the asymmetrical cyclic movement of both legs during running on a curved path with a small radius is distinctively different from the movement of running on a straight path with a tilt.

The asymmetrical cyclic movement of each leg during RC can cause the distinctive characteristics in the vertical component of the angular momentum of the whole body in the moving coordinate system as well as its ML' component in the inclined coordinate system. The changing patterns of the angular momenta of the right and left legs during RC were opposite in phase to each other, while those during RS were in the same phase. To focus on the leg movement causing these contrastive characteristics,
trajectories of the right and left leg CM throughout the stride cycle of RC and RS were shown in Figure 5. The trajectories of each leg CM during RS located on each side of the AP axis during RS showed that the swing movement of each leg was symmetrical about the whole-body CM. In contrast, the trajectories of both the legs during RC located on the right side of the AP axis as viewed from the backside of the subjects indicated that the subjects swung their left leg in their right side because of the great inclination of their whole body. These observations suggest that the distinctive changing patterns of the angular momenta of the right and left legs in the opposite phase to each other are caused by the swing movements of both legs on the same side of the whole-body CM. As an additional finding, the left leg CM during RC moved on an elliptical trajectory in the CW direction, while the right leg CM during RC and both the right and left leg CM during RS moved reciprocally (Figure 5). The left leg moving on the elliptical trajectory during RC possesses a large angular momentum in the CW direction during a backward-swing phase and the small angular momentum in the CCW direction during a forward-swing phase. Thus, considering a total amount of a rotational effect throughout the stride cycle, the elliptical movement of the left leg in the CW direction generates the rotational effects in the CCW direction to the other segments regardless of the external moments. This is a rotational interaction between the segments in the whole-body system, separated from the change of the angular momentum of whole-body generated by the external moments. The change in the angular momentum of a segment during running is caused by a change in the total amount of angular momentum in the system and/or the rotational interaction between the segments in the whole-body system. These observations suggest that sufficient angular momentum of the head and trunk to continue facing the running direction while running on a curved path in the CCW direction was partly provided by the elliptical movement of the left leg in the CW direction (Figure 6).

The present results reveal the differences in the cyclic movement of both the legs between running on a curved path with a small radius and that on a straight path. This finding indicates that an increase in the running speed on the curved path needs not only established training to improve the ability of sprinting on a straight path, but also a learning and refining of the specific movement while running on a curved path with a small radius. Since runners sprinting on a straight path swing their legs on the sagittal planes, they flex/extend their hip and knee joints as well as their plantarflex/dorsiflex their ankle joints. Scores of squat and vertical jumps performed using these joint movements correlate to the ability of sprinting on a straight path (Wisloff et al., 2004). Thus, athletes generally perform training that focuses on the joint movements on the sagittal planes to improve their ability of sprinting on a straight path. However, the left leg CM derailed from the trajectory on the sagittal plan, moving on the elliptical trajectory on the horizontal plane during RC. Since voluntary movement of a knee joint is flexion/extension and the mass of a foot is very small relative to the total mass of a leg, the elliptical movement of the left leg CM on the horizontal plane was achieved by hip abduction/adduction added to the swing on the sagittal plane. Hip abduction/adduction is not generally included in the training to improve the ability of sprinting along a straight path because the reported contribution of hip abduction/adduction in the generation of kinematic energy in the movement direction is only 3% (Novacheck, 1998). Therefore, as an additional training to the established trainings for improving the ability of sprinting on a straight path, the learning of the leg swing movement including left hip abduction/adduction and the training to increase the speed of that movement may be effective in improv-
ing the ability of sprinting on a curved path with a small radius. However, the effectiveness of the additional training of the hip joint movement cannot be confirmed in the present study because no date evaluating the muscle activations was measured. Further research is warranted to analyze muscle activation while sprinting on a curved path with a small radius to establish a new training method focusing on hip abduction/adduction.

It is unclear whether the present results represent the characteristics of athletes in field- or court-based sports because each subject specialized in various sports. Eight in ten subjects habitually performed a sport that frequently involved sprinting on a curved path with a small radius, such as soccer, basketball, American football, and badminton. Although the other two subjects were track and field athletes, they did not show any characteristics that differed from those of the other eight subjects. In addition, the physical characteristics of all the subjects were similar to those of general athletes. Therefore, the present findings can be applicable to athletes in field- or court-based sports. The magnitude of the angular momentum of the right and left leg were different bilaterally, although the cyclic movements of each leg seemed symmetrical. Previous studies of sprinting on a straight path reported bilateral differences in the kinematic parameters (Exell et al., 2012), and the bilateral differences in the kinematics positively correlate with the bilateral differences in the morphological parameters (Seminati et al., 2013). Moreover, muscle strength of the quadriceps and hamstrings is different between the dominant and non-dominant side (Lanshammar and Ribom, 2011). Based on these previous studies, the bilateral difference in the angular momentum of each leg during RS may be caused by the asymmetrical characteristics commonly present in the movement of all the subjects because of the leg dominance in the same side for all subjects. The present findings were based on a comparison of the parameters between RS and RC; therefore, the bilateral difference of the angular momentum during RS may not affect the findings about the mechanism of the whole-body movement while running on a curved path. The running speed and the path radius during RS were set at 5 m/s and 5 m, respectively, regardless of the sprinting ability of each subject. The circular path with a 5-m radius was employed as the minimal path on which the subjects could run at 5 m/s without unusual movements based on a preparatory experiment. Thus, the effort level during RC must have been nearly maximal. Therefore, the present finding can be applicable to the movements with maximal effort performed in an actual game of field or court-based sports.

5. Conclusion

The present study aimed to determine how runners sprinting along a curved path with a small radius could rotate their whole-body about the vertical axis to continue facing the ever-changing running direction. The results demonstrate that the asymmetrical cyclic movement of the whole body while sprinting on a curved path with a small radius differ from that while sprinting on a straight path with a tilt, characterized by the swing movement of the inside leg at higher speed than that of the outside leg. The distinctive mechanism that allowed the runner to keep facing the ever-changing running direction while springing on a curved path with a small radius is revealed as the reactional rotation effect generated by the inside leg movement on an elliptical trajectory in the direction opposite to that of the path curve.

References