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Lumbar axial torque actively induces trunk axial rotation during sidestep cutting manoeuvre: Insight to expand the trunk control concept

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ABSTRACT

Core stability is widely recognised as 'the body's ability to maintain or resume an equilibrium position of the trunk after perturbation'. As such, large excursions of the trunk during controlled activities are believed to be the result of poor trunk control. Here, we show that the axial torque actively induces the trunk axial rotation (the thoracic rotation relative to the pelvis) rather than minimise the axial rotation during sidestep cutting. We analysed the kinematic and kinetic data of 90° sidestep cutting with maximal effort by 10 physically active men. The thorax rotated toward the objective direction prior to the pelvis, resulting in the trunk axial rotation with the peak angle of 21.0 ± 6.0°. Lumbosacral axial torque was exerted toward the objective direction during the early stance phase, and it was then exerted inversely during the late stance and flight phases, which was consistent with the increase/decrease in the trunk axial rotation velocity. In the early stance phase, the absolute integrated component of the lumbosacral axial torque for pelvic rotation (0.074 ± 0.033 Nms/kg) was significantly larger than any other integrated component. In the late stance and flight phases, the lumbosacral axial torque mainly rotated the pelvis. The results indicate that the axial torque is exerted to actively induce the trunk axial rotation rather than minimise the trunk movement, suggesting that the trunk control concept probably should include not only stabilising but also actively moving the trunk.

1. Introduction

Various team/court sport players are required to execute cutting manoeuvres (Bloomfield et al., 2007; Brughelli et al., 2008). Cutting has two mechanical requirements: changing the centre of mass (CoM) velocity to the objective direction ("deflection") and rotating the body in the transverse plane to align with the objective direction (Jindrich et al., 2006). This study focused on transverse rotation, especially the rotational behaviour of the central part of the human body, the trunk.

The trunk is frequently described as the 'core'. Core stability is seen as being pivotal for efficient biomechanical function (Kibler et al., 2006). Core stability was defined as 'the body's ability to maintain or resume an equilibrium position of the trunk after perturbation' (Zazulak et al., 2007), which is widely adopted (Borghuis et al., 2011; Jamison et al., 2013). Zazulak et al. (2007) interpreted the large trunk excursion in a trunk perturbation test as the deficits in neuromuscular control of the trunk. The 'trunk control' ability has been evaluated/trained via the maintenance/resumption of trunk position during tasks such as sudden force release (Jamison et al., 2012), lateral reactive jump (Weltin et al., 2015) and unstable surface drills (Zazulak et al., 2008). This is based on the phrase 'proximal stability for distal mobility' (Kibler et al., 2006), and it is recommended to keep the trunk stability during cutting (Hewett et al., 2009; Sasaki et al., 2011).

Recently, some studies have reported that trunk movement should not always be minimised. Jamison et al. (2013) implied that stiffening the spine by increased co-contraction of the trunk muscles increased knee injury risk. Edwards et al. (2017) observed that athletes with larger trunk excursion showed better cutting performance than athletes with smaller excursion, in which the effect size of the trunk axial rotation excursion was the largest. A recent study (Edwards et al., 2017) used the term 'decreased trunk control' as larger trunk excursion and concluded that better performance is related to 'decreased trunk control'. Although trunk movement should not always be minimised, the interpretation (Edwards et al., 2017) suggests that trunk movement during cutting is recognised as the result of other actions and poor trunk

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control. There are many situations where large trunk excursions are beneficial (such as an avoidance from a defender), and based on this current trunk control concept, large trunk excursions would be interpreted as the result of poor trunk control, as with Edwards et al. (2017). However, if the trunk exerts larger torque than the amount needed to cancel out other actions, the axial torque can induce trunk axial rotation. In this case, trunk axial rotation would not be caused by the poor trunk control but by one's torque exertion. To address this possibility, the trunk rotational behaviour during sidestep cutting should be investigated biomechanically, but to our best knowledge, no study has examined this in detail.

This study aimed to expand the understanding of trunk control during sidestep cutting. We hypothesised that the trunk axial rotation is the result of trunk kinetics rather than the lower-limb actions (i.e. hip joint kinetics). To test our hypothesis, we analysed the axial torque and compared its action on the pelvis with lower-limb actions.

2. Methods

2.1. Experimental data

Experimental data were taken from our previous study (Sado et al., 2019a), which examined a different topic (pelvic oblique in the frontal plane). Details of the experiment can be found elsewhere (Sado et al., 2019a). We explained the summary here.

Participants included 10 physically active men without injury [age, 26 ± 3 years (mean ± SD); height, 1.78 ± 0.05 m; weight, 69.5 ± 9.5 kg)]. All participants provided written informed consent. Experimental procedures were approved by the Human Research Ethics Committee of the University of Tokyo, Japan (reference number: 575).

The marker set can be found elsewhere (Sado et al., 2019a). In this marker set, three-dimensional kinematics of each of the thoracic, lumbar, and pelvic segments were captured by the markers independently attached to each segment. After static trial, functional trials for hip and knee joint centre calculations, and a 15-min self-directed warm-up, the participants performed a cutting task: running (approximately 8 m) to a force platform and cutting to the right with left leg stance on the force platform. They were instructed to quickly cover the distance from a photocell sensor line 3 m before the platform to 3 m after the platform. Three successful trials were captured and analysed.

An 8-camera three-dimensional motion capture system (Motion Analysis Corporation, CA), at a sampling rate of 200 Hz, and two force platforms (Force Plate 9281E, Kistler, Winterthur, Switzerland), at a sampling rate of 2000 Hz, recorded the kinematic and ground reaction force (GRF) data; these data were synchronised with the motion capture system. The $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ axes of the global coordinate system (GCS) defined the mediolateral, anteroposterior, and superoinferior directions, respectively.

2.2. Data analysis

Data were analysed from the left leg contact on the force platform to the right leg contact. The analysis phase was divided into early stance phase (from the left leg contact to the mid-stance), late stance phase (from the mid-stance to the left leg toe-off), and flight phase (from the left leg toe-off to the right leg contact). Instants of left leg contact and toe-off were identified from the onset of the vertical GRF (threshold, 10 N). The instant of the mid-stance was defined as the midpoint between the instants of the left leg contact and toe-off. The right leg contact was identified with kinematic method shown by Nagahara and Zushi (2013).

The smoothing of kinematic and kinetic data, joint centre definitions, and the inertial parameters estimations are shown by Sado et al. (2019a). Based on the anatomical landmark positions, a right-handed local segment coordinate system (SCS) for each segment and a joint coordinate system (JCS) for each joint were defined in each frame. Details of the SCS and JCS definitions were consistent with those of Sado et al. (2017a). Thoracic and pelvic angles were calculated as Cardan angles relative to the GCS (rotation-sequence: $\boldsymbol{x}$ (anteroposterior tilt) – $\boldsymbol{y}$ (lateral obliquity) – $\boldsymbol{z}$ (rotation)). The trunk angle was calculated as the Cardan angle of the thorax SCS relative to the pelvic SCS (rotation-sequence: $\boldsymbol{x}$ (extension/flexion) – $\boldsymbol{y}$ (lateral-flexion) – $\boldsymbol{z}$ (axial-rotation)).

A bottom-up inverse dynamics was used to calculate the lumbosacral and bilateral hip internal torques (i.e., the calculation from feet to pelvis), which was validated by Dumas et al. (2015). Specifically, the equations of motion for the pelvis to calculate the lumbosacral kinetics are explained in the supplemental material. Each anatomical torque (lumbosacral extension, lateral flexion, and axial torque) was calculated by the transformation of the joint torque vector into JCS (Desroches et al., 2010).

We calculated the component of the pelvic rotation ($ROT_{j,axis}$) of each joint torque similar to that by Sado et al. (2017, 2019):

$$ROT_{j,axis} = \boldsymbol{e}_{\mathbf{zpel}} \cdot \left(\tau_{j,axis}\boldsymbol{e}_{\boldsymbol{j},\boldsymbol{axis}}\right) \quad (1)$$

where $\boldsymbol{e}_{\mathbf{zpel}}$ is the unit vector along the pelvic superoinferior axis and $\tau_{j,axis}$ is the component of the joint torque in the direction of unit vector $\boldsymbol{e}_{\boldsymbol{j},\boldsymbol{axis}}$ of the JCS. The moment of joint force on the pelvis at joint j around the pelvic superoinferior axis ($ROT_{j,\mathrm{JF}}$) was calculated as follows:

$$ROT_{j,\mathrm{JF}} = \boldsymbol{e}_{\mathbf{zpel}} \cdot \left(\boldsymbol{r}_{\mathbf{CoM}\to\boldsymbol{j}} \times \boldsymbol{f}_{\boldsymbol{j}}\right) \quad (2)$$

where $\boldsymbol{r}_{\mathbf{CoM}\to\boldsymbol{j}}$ is the relative position vector from the pelvic CoM to joint j and $\boldsymbol{f}_{\boldsymbol{j}}$ is the vector describing the joint force acting on the pelvis at joint j. During the early stance, late stance, and flight phases, each component of the pelvic rotation was integrated to quantify the effect of each joint torque or joint force on pelvic rotation.

For each participant, the mean value of three trials was used for comparisons. Data normality was assessed using the Shapiro–Wilk test. After normality was confirmed, to examine whether the action of axial torque on the pelvis was larger than lower-limb action during the early stance phase (i.e., when the trunk axial rotation angular velocity increased), we compared the absolute integrated component of the pelvic rotation caused by the lumbosacral axial torque and any other component by the paired t-test. To control family-wise error rates in multiple comparisons, the alpha level was adjusted using Holm's method (Holm, 1979). Overall statistical significance was set at $\alpha < 0.05$. The effect size of each comparison was determined using Cohen's d.

3. Results

The thorax rotated toward the objective direction during the overall stance phase (Fig. 1a and b), whereas the pelvis rotated from the late stance to flight phases (Fig. 1c and d). As a result of the stepwise rotations, the trunk axially rotated during the overall stance phase (Fig. 1d; peak value, 21.0 ± 6.0°). During the early stance phase, the axial rotation angular velocity toward the objective direction increased (Fig. 1e; peak value, 251.7 ± 37.9°/s), and the lumbosacral axial torque acted toward the objective direction (Fig. 2). During the late stance and flight phases, the trunk axial rotation velocity decreased (Fig. 1e), and the lumbosacral axial torque was exerted toward inverse to the objective direction (Fig. 2).

During the early stance phase, the left hip axial torque acted to rotate the pelvis toward the objective direction (Fig. 3e and 4a;

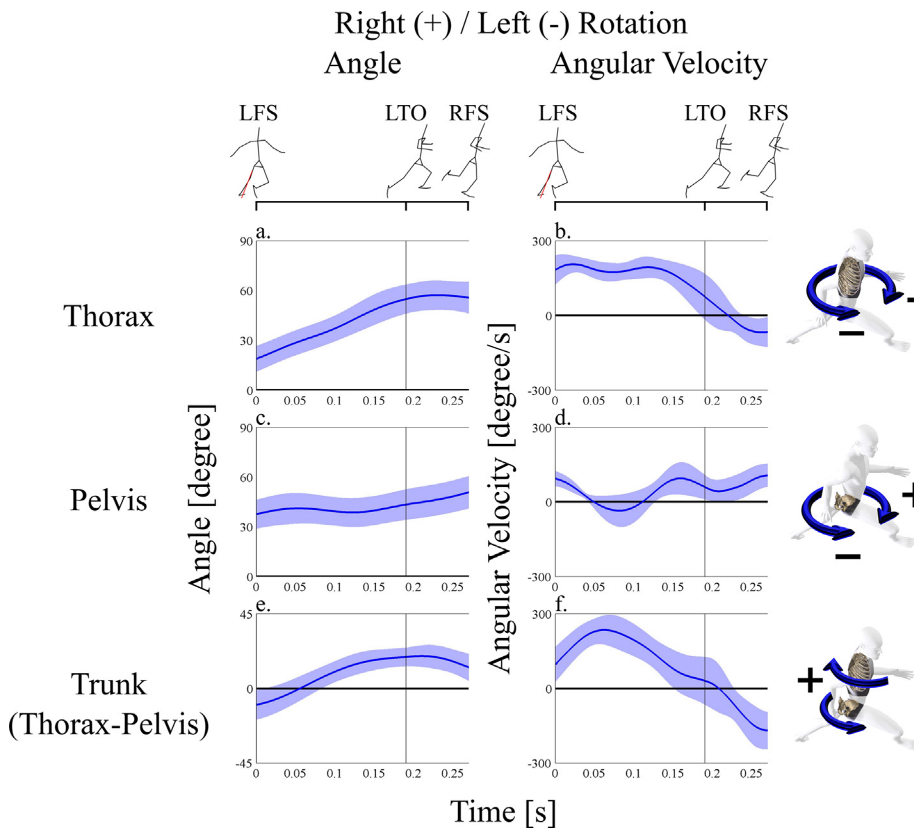

Fig. 1. Ensemble averages of the thoracic rotation, pelvic rotation, and trunk axial rotation (thoracic rotation relative to pelvic rotation) angles (a, c, e) and angular velocities (b, d, f) during a sidestep cutting. LFS, left foot strike; LTO, left toe-off; RFS, right foot strike.

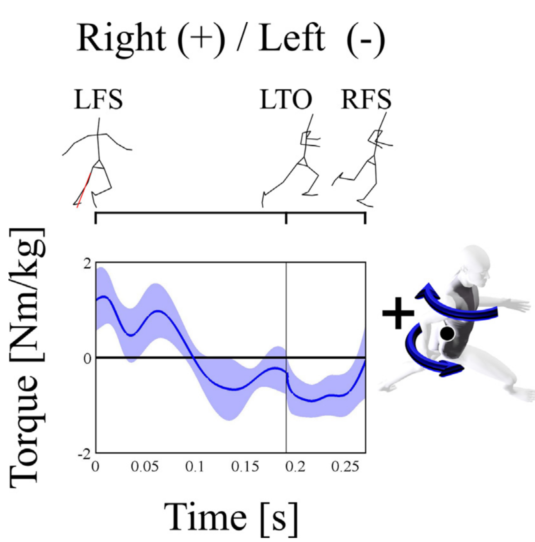

Fig. 2. Ensemble average of the lumbosacral axial torque during a sidestep cutting. LFS, left foot strike; LTO, left toe-off; RFS, right foot strike.

integrated value, 0.052 ± 0.029 Nms/kg), while the lumbosacral axial torque acted toward inverse to the objective direction (Figs. 3b and 4a; integrated value, −0.074 ± 0.033 Nms/kg). The absolute value of the integrated component of axial torque was significantly larger than that of any other component (Fig. 5, p = 0.000–0.009, d = 0.69–3.07). During the late stance and flight phases, the lumbosacral axial torque mainly rotated the pelvis toward the objective direction (Fig. 3b and 4b and c; integrated value, 0.039 ± 0.030 Nms/kg for the late stance phase and 0.048 ± 0.016 Nms/kg for the flight phase). Any other integrated component was ≤0.007 Nms/kg for the late stance (Fig. 4b) and ≤0.018 Nms/kg for the flight phases (Fig. 4c).

During the late stance phase, the anterior component of the stance hip joint force on the thigh, expressed in the pelvic SCS, increased from −0.53 ± 1.88 to 5.06 ± 1.29 N/kg (Fig. 6b). Simultaneously, its power on the thigh increased (Fig. 6c).

4. Discussion

We hypothesised that the trunk axial rotation during cutting was the result of trunk kinetics rather than lower-limb actions, which was confirmed via detailed kinetic analysis. Our findings have new insights to expand the trunk control concept.

Core stability has been recognised as to maintain an equilibrium trunk position (Jamison et al., 2013; Kibler et al., 2006; Zazulak et al., 2007). Trunk control is explained using this statement defining core stability (Edwards et al., 2017; Jamison et al., 2012), and the trunk control ability has been evaluated/trained via maintaining/resuming trunk during unstable exercises (Jamison et al., 2012; Weltin et al., 2015; Zazulak et al., 2008). A recent study (Edwards et al., 2017) concluded that the trunk excursion during cutting is the result of poor trunk control. They suggest that the current trunk control concept does not include the behaviour actively moving the trunk, which would lead to the interpretation of the large trunk excursion during cutting as the poor trunk control. However, the lumbosacral axial torque was consistent with the increase/decrease in the trunk axial rotation velocity. Additionally, although this trunk axial rotation toward objective direction is the thoracic rotation toward objective direction relative to the pelvis, the hip kinetics on the pelvis during the early stance phase (when the trunk axial rotation velocity increased)

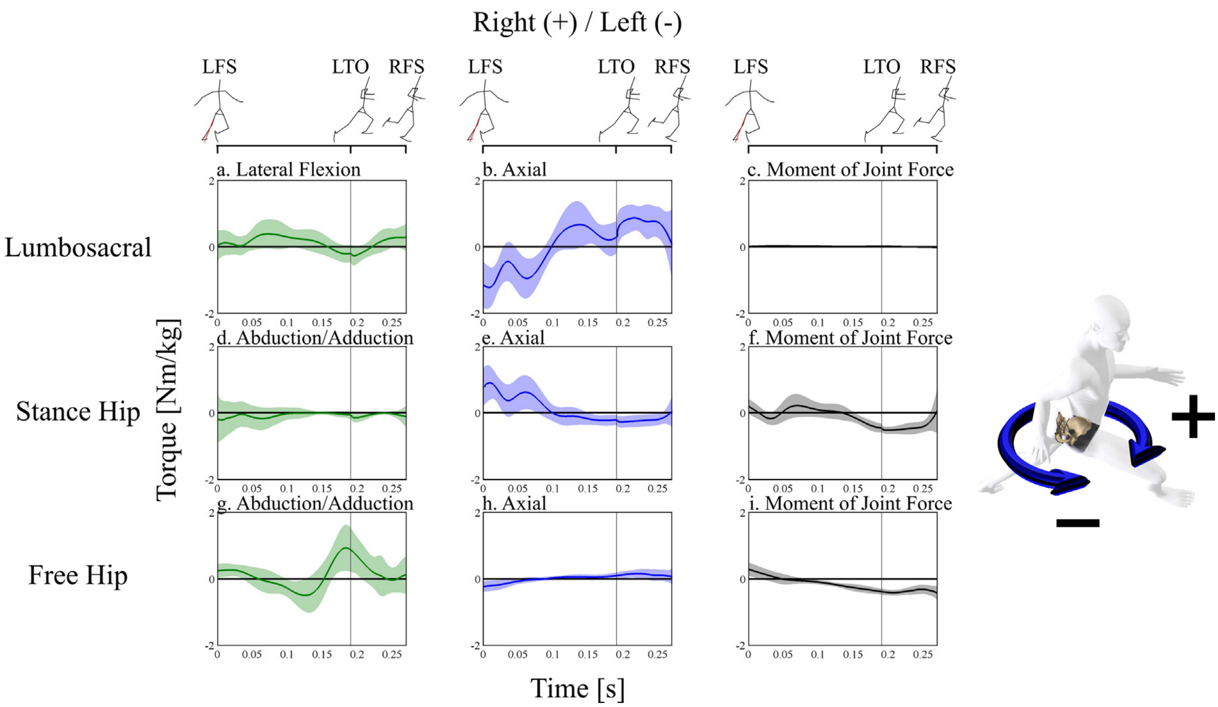

Fig. 3. Ensemble averages of the components contributing to pelvic rotation during a sidestep cutting. LFS, left foot strike; LTO, left toe-off; RFS, right foot strike. The components caused by hip and lumbosacral flexion/extension torques are not shown because, in joint coordinate system definitions, the axes of the hip and lumbosacral flexion/extension equivalent to the pelvic mediolateral axis are orthogonal to the axis of the pelvic rotation (pelvic superoinferior axis) and so do not include components of pelvic rotation (Sado et al., 2019a, 2017b).

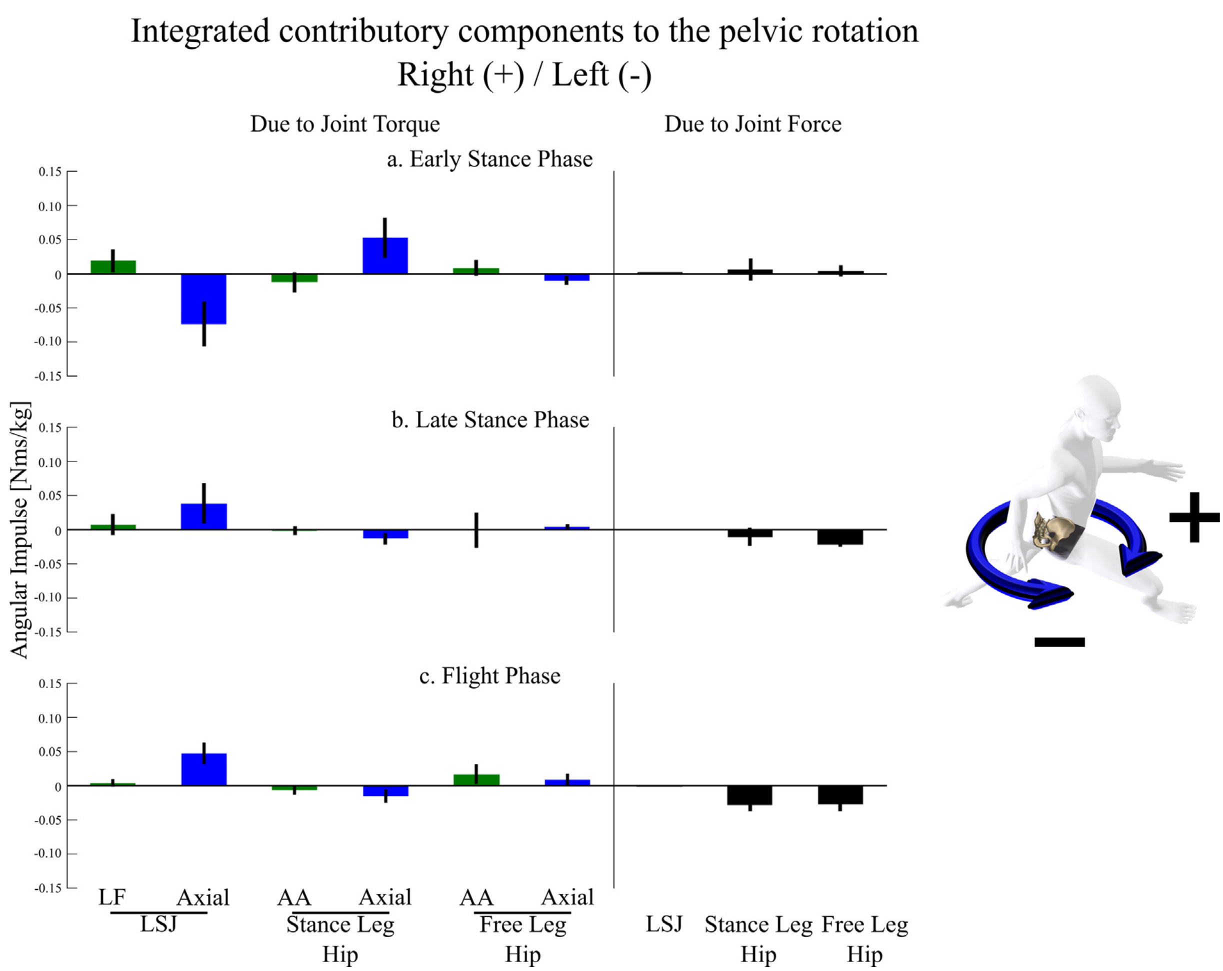

Fig. 4. Integrated components contributing to pelvic rotation during a sidestep cutting. LF, lateral flexion; AA, abduction-adduction; LSJ, lumbosacral joint.

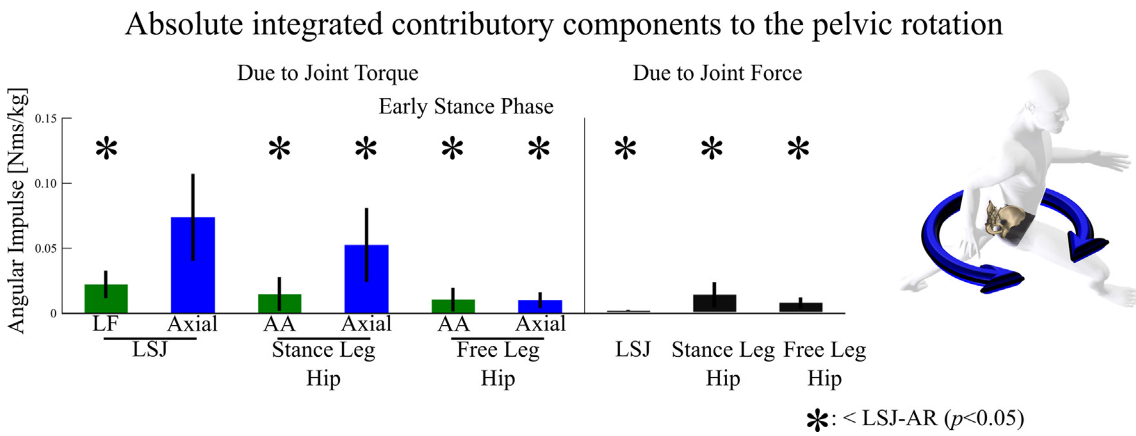

Fig. 5. Absolute integrated components contributing to pelvic rotation during early stance phase in a sidestep cutting. This figure shows the absolute values in Fig. 4a. LF, lateral flexion; AA, abduction-adduction; LSJ, lumbosacral joint; *, significant smallness from the component due to lumbosacral axial torque based on the paired t-tests with Holm's method for p-value adjustments.

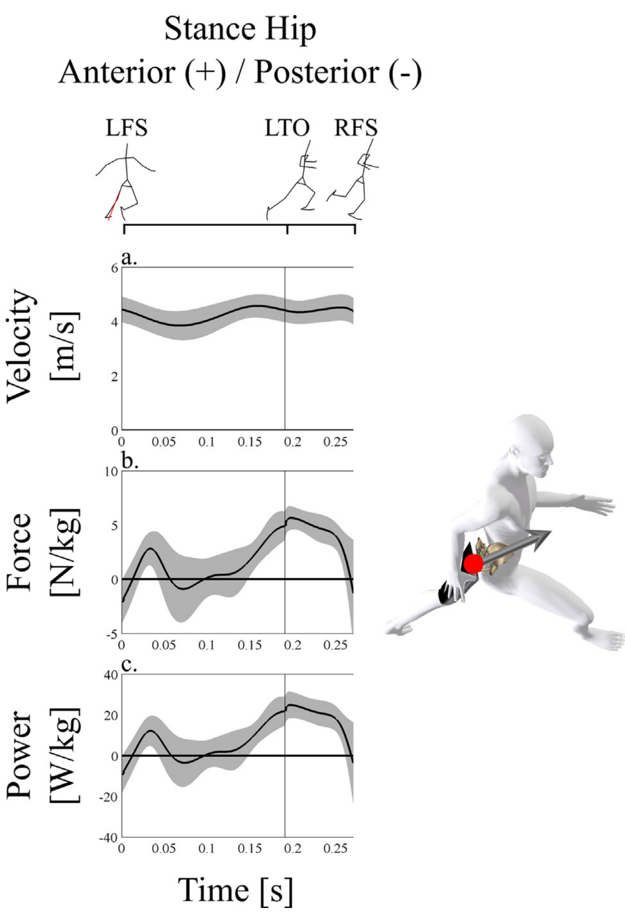

Fig. 6. Ensemble average of the anteroposterior components of the stance hip joint velocity (a), joint force (b), and joint force power (c) during a sidestep cutting. LFS, left foot strike; LTO, left toe-off; RFS, right foot strike. Data are expressed in the pelvic segment coordinate system.

acted to rotate the pelvis toward the objective direction (i.e., inverse action to the trunk axial rotation). This means that the lower-limb action restrained the trunk axial rotation rather than promote it. Furthermore, the absolute integrated component of the lumbosacral axial torque to pelvic rotation was significantly larger than any other component. If the current trunk control concept is always true, the action of axial torque on the pelvis would be smaller than or equal to the lower-limb actions. Thus, our results indicated that, contrary to the current trunk control concept, the axial torque actively induce trunk axial rotation.

Trunk axial rotation consisted of thoracic rotation before pelvic rotation. During the early stance phase, the lumbosacral axial torque and stance hip axial torque cancelled out each other's action on the pelvis; thus, the axial torque induces only the thoracic rotation toward the objective direction during the early stance phase (Fig. 7). Edwards et al. (2017) reported that athletes having better cutting performance showed larger transverse trunk excursion. Further, we add the detail of the trunk rotational behaviour (stepwise rotation from the thorax to the pelvis) and its kinetic mechanism. Below, we discuss why larger axial rotation excursion might relate to better cutting performance.

If the trunk behaves as a single rigid body, the mass is approximately half of the whole-body mass (de Leva, 1996; Dumas et al., 2007), meaning large inertia. In the model dividing the trunk into three segments, the masses of the thorax and pelvis are approximately 30% (Dumas et al., 2015) and 15% (Dumas et al., 2007), respectively. Thus, stepwise rotations might induce smaller inertia at each instant, which might induce faster rotation of each segment. The pelvis pulled the stance leg toward the objective direction before toe-off simultaneously to pelvic rotation. The faster pelvic rotation caused by the stepwise rotation might assist for a faster leg recovery by pulling the stance leg, similar to sprinting (Sado et al., 2019b, 2017b).

We examined how the central part of the body rotates during cutting. However, this study cannot quantify the performance improvements of the stepwise rotations. Future studies, such as the comparison between cutting with and without limiting trunk excursion by using an orthosis or a training experiment, might clarify the effects of trunk rotational behaviour on the cutting performance. Moreover, we examined only one cutting angle. The cutting angle might affect the trunk rotational behaviour, which is also the limitation and important future theme. Furthermore, although we analysed the pre-planned cutting and the trunk had axial rotation angular velocity toward objective direction at the left leg contact, many situations need to cut suddenly in sports. The preparation for sidestep cutting varies depending on pre-planned or unanticipated situations, which might influence the lumbar kinetics during cutting and its preparation. This should be examined in future experiments. Finally, we did not collect the electromyographic data. The lumbar axial-rotator muscle activities might be useful to expand the understanding of the neuromuscular control in future studies.

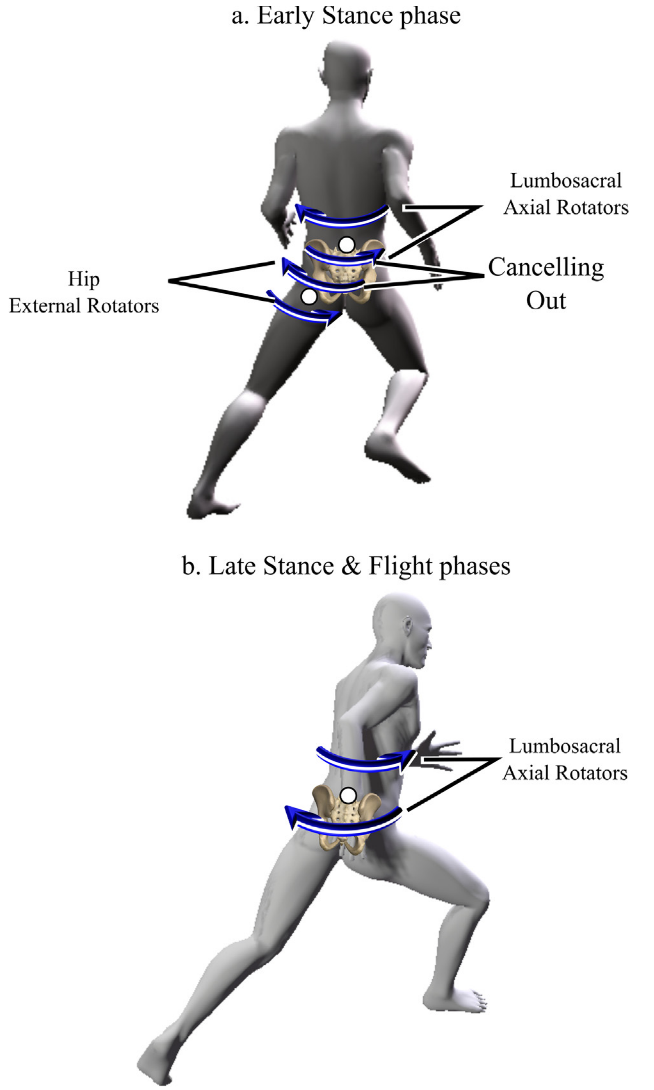

Fig. 7. Schematic representation of the kinetic mechanisms of the stepwise rotations of trunk segments during a sidestep cutting.

In summary, the lumbosacral axial torque exertion during sidestep cutting was consistent with the increase/decrease in trunk axial rotation velocity and the action of the axial torque on the pelvis was larger than any other lower-limb action. We concluded that the axial torque actively induces the trunk axial rotation during sidestep cutting and that the 'trunk control' concept probably should include not only minimising trunk movement but also actively moving the trunk.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2020.110003.

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