SCIENTIFIC JOURNAL OF SPORT AND PERFORMANCE

ORIGINAL ARTICLE

A longitudinal study of three-dimensional pelvic behaviour in maximal sprint running

Kazuki Ota ✉ . *Graduate School of Comprehensive Human Sciences. University of Tsukuba. Tsukuba, Japan.*
Takuya Yoshida. *Japan Institute of Sports Sciences. Tokyo, Japan.*
Yuki Furuhashi. *Graduate School of Comprehensive Human Sciences. University of Tsukuba. Tsukuba, Japan.*
Kotaro Muratomi. *Graduate School of Comprehensive Human Sciences. University of Tsukuba. Tsukuba, Japan.*
Hirohiko Maemura. *Faculty of Health and Sports Science. University of Tsukuba. Tsukuba, Japan.*
Satoru Tanigawa. *Faculty of Health and Sports Science. University of Tsukuba. Tsukuba, Japan.*

ABSTRACT

The kinematics and kinetics of pelvis are associated with sprint performance. In this study, we aimed to investigate the longitudinal changes in the kinematics and kinetics of the pelvis in response to increasing sprinting velocity. Nine male sprinters performed 60 m regular sprints starting from a crouching start position, once a year. A three-dimensional motion analysis was performed to longitudinally investigate the changes in the pelvic movements and force exertion characteristics during sprinting. Sprinting velocity was significantly higher in the post-test than the pre-test. Step frequency was significantly higher in the post-test than the pre-test. The pelvic anterior/posterior tilt angle at stance leg touch-down, stance leg toe-off, and free leg touch-down were significantly smaller in the post-test than the pre-test. The thigh angle of the stance leg at stance leg toe-off and free leg touch-down were significantly smaller in the post-test than in the pre-test. The integrated contributory component of the lumbosacral joint torsion angular impulse during the stance phase was significantly greater in the post-test than the pre-test. This study provided new insights into the longitudinal evaluation of sprint performance in the transverse plane, focusing on pelvic movement and force exertion characteristics.

Keywords: Performance analysis, Longitudinal study, Increase sprint performance, Pelvis, Lumbosacral torsion torque.

Cite this article as:
Ota, K., Yoshida, T., Furuhashi, Y., Muratomi, K., Maemura, H., & Tanigawa, S. (2024). A longitudinal study of three-dimensional pelvic behaviour in maximal sprint running. *Scientific Journal of Sport and Performance*, *3*(3), 370-382. https://doi.org/10.55860/DOUP6264

✉ **Corresponding author.** *Graduate School of Comprehensive Human Sciences, University of Tsukuba. 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8574. Japan.*
E-mail: san.tf.hk@icloud.com
Submitted for publication February 29, 2024.
Accepted for publication April 16, 2024.
Published April 29, 2024.
Scientific Journal of Sport and Performance. ISSN 2794-0586.

doi: https://doi.org/10.55860/DOUP6264

INTRODUCTION

Sprinting is a basic human locomotor activity, and improving sprint performance is important in various competitive sports. Maximal sprinting velocity is a key determinant of sprint performance (Bruggemann and Glad, 1990). Sprinting velocity is determined by step frequency and step length (Hay, 1993), with an inverse relationship existing between them (Hunter et al., 2004). Therefore, achieving high sprinting velocity requires increasing one of the two elements and maintaining the other.

Pelvic lateral flexion toward the free leg side is crucial for determining step length during sprinting (Preece et al., 2016), and this movement is facilitated by the hip abduction torque and free leg side lumbosacral joint lateral flexion torque. Improving the recovery of leg motion during sprinting results in an improvement in step frequency (Chapman and Caldwell, 1983), and this movement is associated with pelvic rotation toward the free leg side (Novacheck, 1998; Sado et al., 2017). The free leg side lumbosacral joint torsional torque contributes significantly to the forward rotation on the pelvis of the stance leg side toward the free leg side in the transverse plane, supporting in the recovery of leg motion of the stance leg (Sado et al., 2017). Therefore, it is reasonable to consider that the hip abduction torque, free leg side lumbosacral joint lateral flexion torque, and torsional torque during sprinting may play an important role in achieving high sprinting velocity. However, existing research, primarily cross-sectional studies, have focused on the relationship between variables and differences in competition levels, and longitudinal studies have not yet investigated the factors influencing step frequency and step length with increasing sprinting velocity.

In the field of sports training, sprinting movement with minimal backside mechanics and optimal frontside mechanics have been proposed to enhance sprinting (Mann and Murphy, 2015). This approach has been found to improve sprint performance (Clark et al., 2020) and prevent hamstring injuries (Mendiguchia et al., 2021). Notably, minimal backside mechanics are important as opposed to optimal frontside mechanics (Haralabidis et al., 2022). A training program focusing on minimal backside mechanics and optimal frontside mechanics resulted in a reduction in the pelvic forward tilt angle during the flight phase and the thigh of the stance leg backward at toe-off during sprinting (Mendiguchia et al., 2021). Therefore, it is reasonable to conclude that the sprinting movement were primarily evaluated in the sagittal plane. However, considering that the pelvic rotation toward the free leg side during sprinting contributes to the improvement in step frequency by assisting the recovery of leg motion (Sado et al., 2017), minimal backside mechanics and optimal frontside mechanics may influence pelvic movements and force exertion characteristics in the transverse plane. Thus, examining pelvic movements and force exertion characteristics through longitudinal data on increased sprinting velocity could offer valuable insights into pelvic function during sprinting and provide practical guidance to improve sprint performance, complementing existing cross-sectional findings.

Therefore, in this study, we aimed to investigate the longitudinal changes in the kinematics and kinetics of the pelvic movement in response to increasing sprinting velocity. We hypothesized that, the pelvic movement and force exertion characteristics in the transverse plane would assist in the recovery of leg motion to achieve high step frequency during sprinting.

METHODS

Participants

This study included nine male sprinters (mean ± standard deviation (SD), age, pre-test: 20.77 ± 1.56 years, post-test: 21.77 ± 1.56 years; height, pre-test: 1.78 ± 0.03 m, post-test: 1.78 ± 0.03 m; total body mass, pre-test: 67.89 ± 3.63 kg, post-test: 68.90 ± 5.26 kg; personal best time in a 100 m sprint, pre-test: 11.06 ± 0.31

s [range, 10.50-11.46 s], post-test: 11.02 ± 0.31 s [range, 10.50-11.46 s]). For 12 sprinters, the measurements were obtained during sprinting; however, only 9 were included in this study due to exclusion of 3 sprinters whose sprinting velocities had decreased. The subjects were members of the university's track and field team who trained regularly for sprinting events (4-5 days per week for at least 5 years) and were free of injury for at least 6 months prior to their participation. Before participating in the study, they received an explanation of the study goals, and informed consent was obtained from them. This study was approved by the ethical committee in the faculty of Health and Sport Sciences, University of Tsukuba, in accordance with the Declaration of Helsinki (approval number: Tai020-1).

Measures

All the subjects wore close-fitting attire and sprinting spikes. Each subject had 47 retro-reflective markers (14 mm in diameter) attached to their trunk and limbs for motion capture (Sado et al., 2017). After 30 min of individualized warm-ups, the subjects performed 60 m sprints from a crouching start with maximal effort to complete two trials, which required either foot to contact one of the three force platforms (Kistler 9287C, 9281E, 9281E, Kistler Instrument AG, Winterthur, Switzerland, total length: 2.1 m) located 50 m from the sprint commencement. Adequate recovery time (at least 5 min) was provided between the trials to avoid fatigue. The post-test measurements were conducted in the same month of the following year as that of the pre-test measurements.

Procedures

We captured three-dimensional coordinates of the reflective marker positions using 26 cameras optical motion capture system (Vicon T20 system, Nexus 2, Vicon Motion Systems, Ltd., Oxford, UK) at 250 Hz. The ground reaction force (GRF) was recorded using three force platforms at a sampling rate of 1000 Hz, synchronized with the motion data. The x-, y-, and z-axes of the global coordinate system (GCS) represented the medial-lateral, anterior-posterior, and superior-inferior directions, respectively. The motion capture volume was 1.0 m × 8.0 m × 2.0 m (width × length × height). Before calculating the joint angles and moments, we filtered the three-dimensional coordinates of the reflective marker positions using a 4th order Butterworth low-pass digital filter (Wells and Winter, 1980) with a cut-off frequency of 20 Hz.

The leg stepping onto the force platform was designated as the "*stance leg*", while the other leg was referred to as the "*free leg*". The step cycle was defined as the period from stance leg touch-down (STD) to free leg touch-down (FTD). We identified the STD and stance leg toe-off (STO) times from the onset of GRF signals, with a GRF threshold set at 15 N. Furthermore, we identified FTD using kinematic methods based on the vertical acceleration of the marker on the free-leg toe (Nagahara and Zushi, 2013). Time-series data each subject was normalized such that the time required for one step cycle was equivalent to 100 %, with the stance and flight phase each being equivalent to 50 %.

We conducted data analysis using MATLAB software version 2021b (Math Works Inc., Natick, MA, USA). The whole-body kinematic model used for the analysis included 15 rigid segments linked by 14 joints (Dumas et al., 2007a, 2007b). Right-handed local segment coordinate systems (SCSs) were defined in each frame. Details regarding the definitions of the lower-limb and pelvic SCSs are provided in a previous study (Dumas et al., 2007a, 2007b). All joint centre of rotation positions were estimated based on the location of reflective markers. Joint centre for the wrist, elbow, ankle, and knee were localized at the midpoint of a line joining the lateral and medial markers. The joint centre of the lower neck, shoulder, lumbosacral, and hip were estimated in each frame of motion using the functional method (Reed et al., 1999). The centre of mass (CoM) and inertial parameters for each segment were estimated using anthropometric data (Dumas et al., 2007a, 2007b). Peak GRF and impulse were normalized by the total body mass. We calculated the contact and flight time based on the number of frames between STD and STO as well as STO and FTD, respectively. Step frequency was defined as the reciprocal of the time required for one step, whereas step length represented the horizontal distance from the CoM at STD to the CoM at FTD. Sprinting velocity was defined as the product of step frequency and step length. We calculated the pelvic and thigh segment angles in the sagittal, frontal, and transverse planes. Three-dimensional angular kinematics were calculated using the Cardan angle sequences; ***X→Y'→Z''*** of the SCSs relative to the GCS. The term "*thigh forward/backward*" was defined as the first rotation of the medial-lateral (x) axis of the right and left thigh SCS. The angular velocity of each segment was calculated as the time derivative of the segment angle profiles.

We established the joint coordinate system (JCS; x_{jnt} y_{jnt} z_{jnt}) at each joint (Grood and Suntay, 1983; Wu et al., 2002). Newton–Euler equations were used to calculate the three-dimensional components of the joint force and torque at the ankle, knee, hip, and lumbosacral joints (Winter, 2009), and the joint torques were calculated using an inverse dynamics approach. The term "*pelvic elevation*" was defined as the rotation of the pelvis around the pelvic anterior-posterior (A-P) axis. Torques calculated at the hip and lumbosacral joints were projected onto the pelvic A-P axis (Sado et al., 2016). The term "*pelvic rotation*" was defined as the rotation of the pelvis around the pelvic superior-inferior (S-I) axis, with torques calculated at the hip and lumbosacral joints were projected onto the pelvic S-I axis (Sado et al., 2017). We calculated the integrated contributory component of the lumbosacral joint torsion angular impulse was calculated as the integral value at the same time as the displacement of the pelvic free leg side rotation angle. The integrated contributory component of the lumbosacral joint torsion angular impulse during the stance and flight phase was calculated as the integral value at the same time as the displacement of the pelvic free leg side rotation angle during the stance and flight phase. The joint torque and angular impulse were normalized by total body mass.

Analysis

The mean, SD, and confidence interval values were calculated for descriptive analysis. All statistical analyses were performed using SPSS version 28 (IBM Corp., Armonk, NY, USA). The normality of the data was assessed using the Shapiro–Wilk test. After normality was confirmed, the Student's paired t-test and Wilcoxon's paired t-test were used to compare the data, with statistical significance set at $p < .05$. According to Cohen (1992), effect sizes can be classified as small (< 0.49), medium (0.50−0.79), and large (> 0.80). According to Field (2005), effect sizes can be classified as small (0.10-0.29), medium (0.30−0.49), and large (> 0.50).

RESULTS

Table 1 presents the mean sprinting velocity, step frequency, step length, contact time, and flight time from the pre-test and the post-test. Sprinting velocity was significantly higher in the post-test than the pre-test (9.20 ± 0.26 m/s vs. 9.42 ± 0.20 m/s, $p = .03$, $d = 0.85$). Although there was no significant difference in step length between the pre-test and the post-test, step frequency was significantly higher in the post-test than the pre-test (4.04 ± 0.18 Hz vs. 4.28 ± 0.26 Hz, $p = .01$, $d = 1.04$). Flight time was significantly shorter in the post-test than the pre-test (0.143 ± 0.013 s vs. 0.134 ± 0.014 s, $p = .03$, $d = 0.86$). Figure 1 presents peak GRF and impulse in the pre-test and the post-test. There was no significant difference in the peak GRF and impulse between the pre-test and the post-test. Figure 2 presents the ensemble average with the SD of the pelvic angle, as well as the angular velocity in the pre-test and the post-test. Table 2 presents the mean pelvic angle in the pre-test and the post-test. The pelvic anterior/posterior tilt angle at STD, STO, and FTD were significantly smaller in the post-test than the pre-test (STD: 6.63 ± 3.01 deg vs. 3.28 ± 4.08 deg, $p = .02$, $d = 0.89$, STO: 9.23 ± 3.72 deg vs. 5.44 ± 3.67 deg, $p = .02$, $d = 0.94$, FTD: 6.71 ± 4.08 deg vs. 2.11 ± 4.82 deg, $p = .01$, $d = 1.09$). Figure 3 presents the ensemble average with the SD of the thigh angle, as well as the angular velocity in the pre-test and the post-test. Table 3 presents the mean thigh angle in the pre-test and the post-test. The thigh angle of the stance leg at STO and FTD were significantly smaller in the pre-test than in the post-test (STO: 30.35 ± 5.74 deg vs. 28.25 ± 5.16 deg, p = .03, d = 0.83, FTD: 6.83 ± 9.16 deg vs. −0.71 ± 10.91 deg, p = .02, d = 0.88). The thigh angle of the free leg at STD and STO were significantly smaller in the post-test than in the pre-test (STD: 4.16 ± 5.80 deg vs. −5.39 ± 8.17 deg, p = .01, d = 1.00, STO: −66.20 ± 6.84 deg vs. −71.85 ± 4.07 deg, p < .01, d = 1.17). Figure 4 presents the ensemble average of the individual contributory components of pelvic elevation in the pre-test and the post-test. Figure 5 presents the ensemble average of the individual contributory components of pelvic rotation in the pre-test and the post-test. Figure 6 presents the integrated contributory components of the lumbosacral joint torsion angular impulse during the total, stance, and flight phase in the pre-test and the post-test. The integrated contributory component of the lumbosacral joint torsion angular impulse during the total and the stance phase were significantly greater in the post-test than the pre-test (total: 0.092 ± 0.019 Nms/kg vs. 0.104 ± 0.021 Nms/kg, p = .03, d = 0.82, stance phase: 0.043 ± 0.015 Nms/kg vs. 0.055 ± 0.017 Nms/kg, p = .02, d = 0.95).

Table 1. Mean step parameters and height of centre of mass (±SD) from the Pre and Post.

Variables	**Pre （95 % CI）**	**Post （95 % CI）**	***p*-value**	**Effect size (*d*)**
Sprinting speed (m/s)	9.20 ± 0.26 9.03 – 9.36	9.42 ± 0.20 9.29 – 9.53	.03*	0.85
Step frequency (Hz)	4.04 ± 0.18 3.94 – 4.16	4.28 ± 0.26 4.12 – 4.44	.01*	1.04
Step length (m)	2.28 ± 0.10 2.21 – 2.34	2.21 ± 0.15 2.12 – 2.30	.10	0.61
Contact time (s)	0.105 ± 0.004 0.103 – 0.107	0.100 ± 0.008 0.096 – 0.106	.10	0.60
Flight time (s)	0.143 ± 0.013 0.135 – 0.150	0.134 ± 0.014 0.125 – 0.141	.03*	0.86

*Note. SD: standard deviation, CI: confidence interval, * : p < .05.*

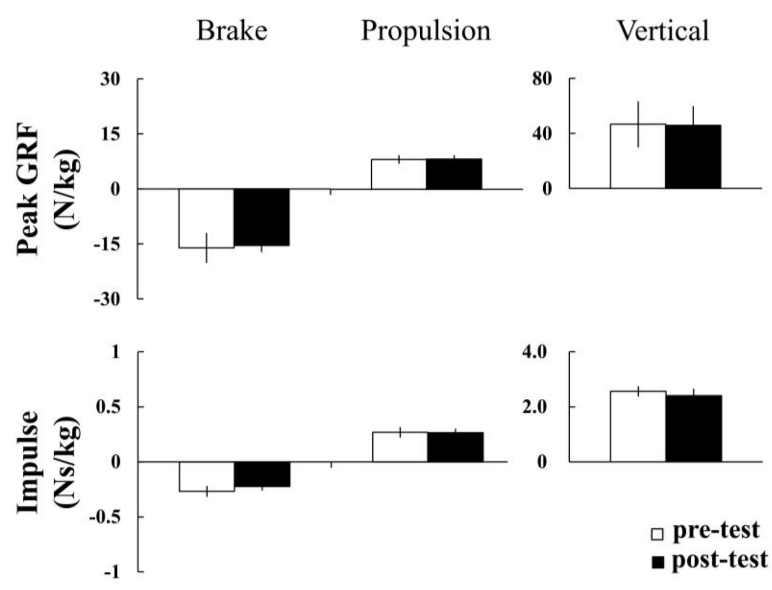
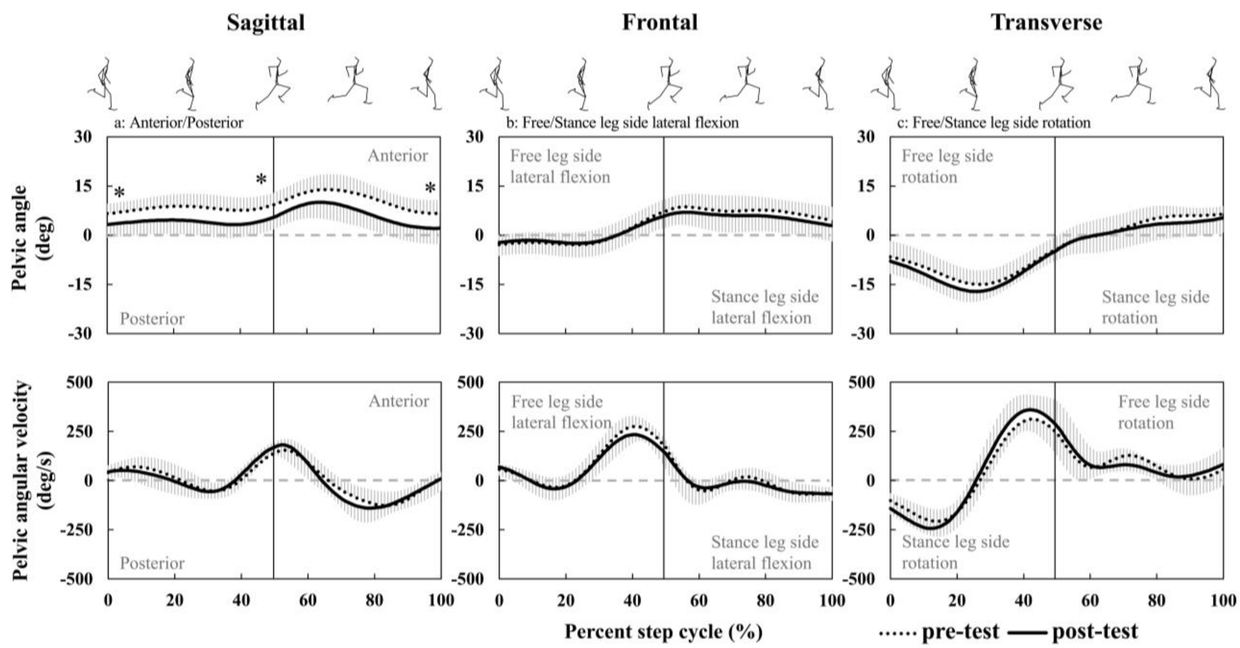


Figure 1. Peak ground reaction force (top) and impulse (bottom) in the pre-test and the post-test. GRF: ground reaction force.

Table 2. Mean pelvic angle (±SD) from the Pre and Post.

Variables	Pre （95 % CI）	Post （95 % CI）	*p*-value	Effect size (*d*)
Sagittal				
Anterior/Posterior angle at STD (deg)	6.63 ± 3.01 (4.54 – 8.42)	3.28 ± 4.08 (0.88 – 5.76)	.02*	0.89
Anterior/Posterior angle at STO (deg)	9.23 ±3.72 (6.99 – 11.67)	5.44 ± 3.67 (3.13 – 7.67)	.02*	0.94
Anterior/Posterior angle at FTD (deg)	6.71 ± 4.08 (4.18 – 9.26)	2.11 ± 4.82 (-0.68 – 5.17)	.01*	1.09
Frontal				
Free/Stance leg side lateral flexion angle at STD (deg)	-2.86 ± 3.04 (-4.87 – -1.18)	-2.23 ± 2.49 (-3.18 – -0.70	.57	0.19
Free/Stance leg side lateral flexion angle at STO (deg)	7.30 ± 3.72 (4.76 – 9.42)	5.95 ± 3.49 (3.59 – 7.99)	.12	0.56
Free/Stance leg side lateral flexion angle at FTD (deg)	4.61± 1.99 (3.52 – 5.84)	2.91 ± 3.63 (0.82 – 5.30)	.24	0.41
Transverse				
Free/Stance leg side rotation angle at STD (deg)	-6.63 ± 4.91 (-10.16 – -3.98)	-7.93 ± 3.89 (-10.66 – -5.70)	.13	0.49
Free/Stance leg side rotation angle at STO (deg)	-4.25 ± 4.04 (-7.26 − -2.10)	−4.61 ± 3.01 (-6.33 – -2.62)	.76	0.10
Free/Stance leg side rotation angle at FTD (deg)	6.51 ± 2.44 (5.01 8.10)	5.31 ± 4.54 (2.59 – 8.18)	.39	0.30

*Note. SD: standard deviation, CI: confidence interval, * : p < .05. STD: stance leg touch-down, STO: stance leg toe-off, FTD: free leg touch-down.*



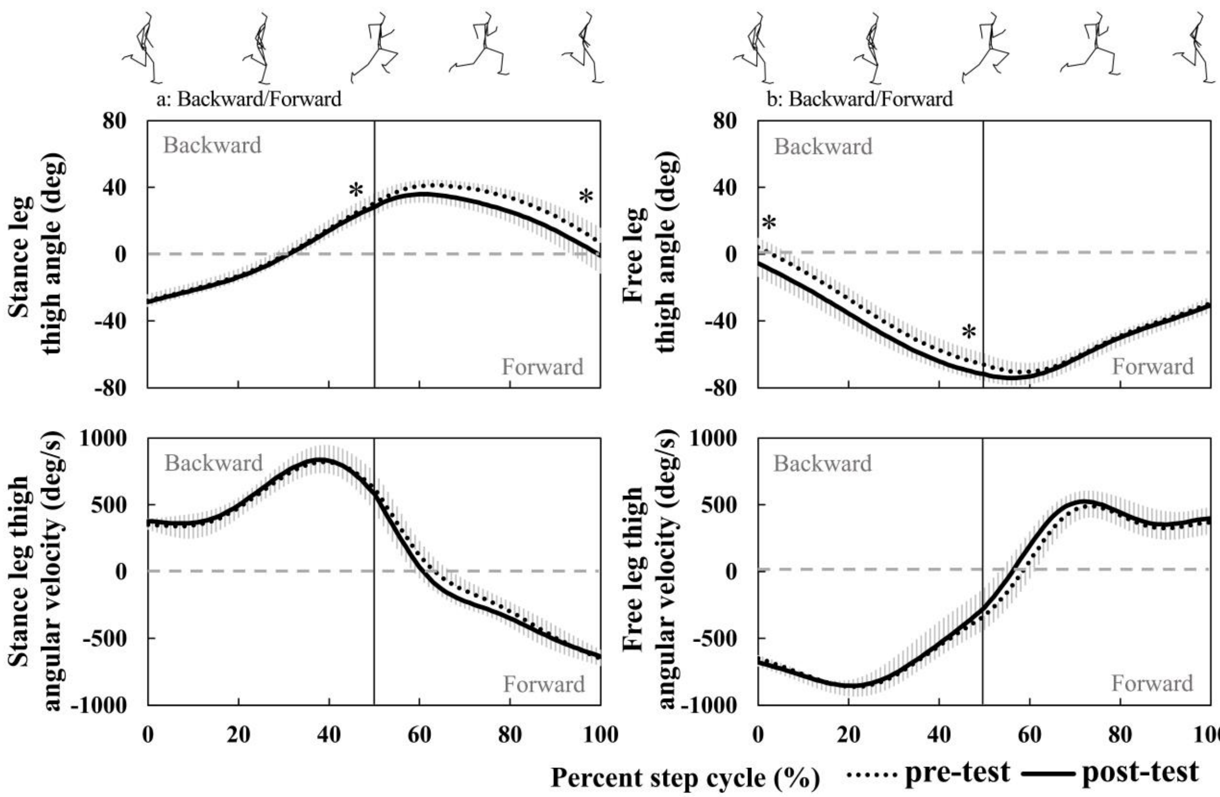
*Note. The vertical line is 50 % of the percent step cycle and represents the toe off instant for each test. *: p < .05.*

Figure 2. Ensemble averages with standard deviation of the pelvic angle and angular velocity in the sagittal (left), frontal (centre) and transverse plane (right) for the pre-test (dashed line) and the post-test (solid line).

Table 3. Mean thigh angle (±SD) in the Pre and the Post.

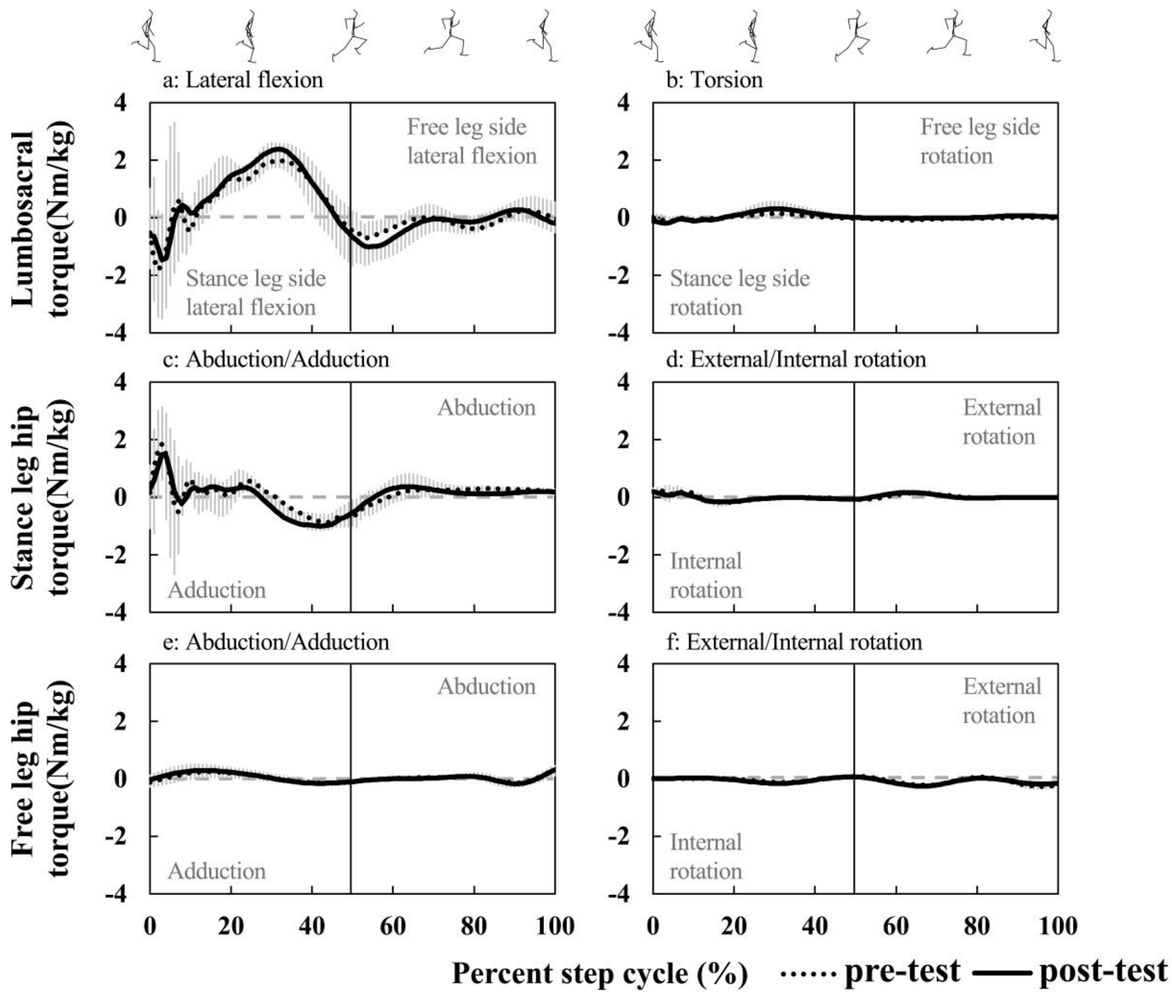
Variables	Pre （95 % CI）	Post （95 % CI）	*p*-value	Effect size (*d*)
Stance leg				
Forward/Backward angle at STD (deg)	-27.90 ± 4.03 (-30.62 – -25.60)	-28.54 ± 2.96 (-30.38 – -26.82)	.62	0.16
Forward/Backward angle at STO (deg)	30.35 ± 5.74 (26.91 – 33.68)	28.25 ± 5.16 (24.91 – 31.22)	.03*	0.83
Forward/Backward angle at FTD (deg)	6.83 ± 9.16 (0.98 – 12.49)	-0.71 ± 10.91 (-7.63 – 5.28)	.02*	0.88
Free leg				
Forward/Backward angle at STD (deg)	4.16 ± 5.80 (0.91 – 7.88)	-5.39 ± 8.17 (-10.15 – -0.53)	.01*	1.00
Forward/Backward angle at STO (deg)	-66.20 ± 6.84 (-70.24 – -61.82)	-71.85 ± 4.07 (-74.53 – -69.39)	<.01*	1.17
Forward/Backward angle at FTD (deg)	-29.35 ± 4.30 (-32.05 – -26.72)	-30.46 ± 4.34 (-33.00 – -27.85)	.43	0.27

*Note. SD: standard deviation, CI: confidence interval, * : p < .05. STD: stance leg touch-down, STO: stance leg toe-off, FTD: free leg touch-down.*



*Note. The vertical line is 50 % of the percent step cycle and represents the toe off instant for each test. *: p < .05.*

Figure 3 Ensemble averages with standard deviation of the thigh angle and angular velocity for the pre-test (dashed line) and the post-test (solid line).



Note. The vertical line is 50 % of the percent step cycle and represents the toe off instant for each test.

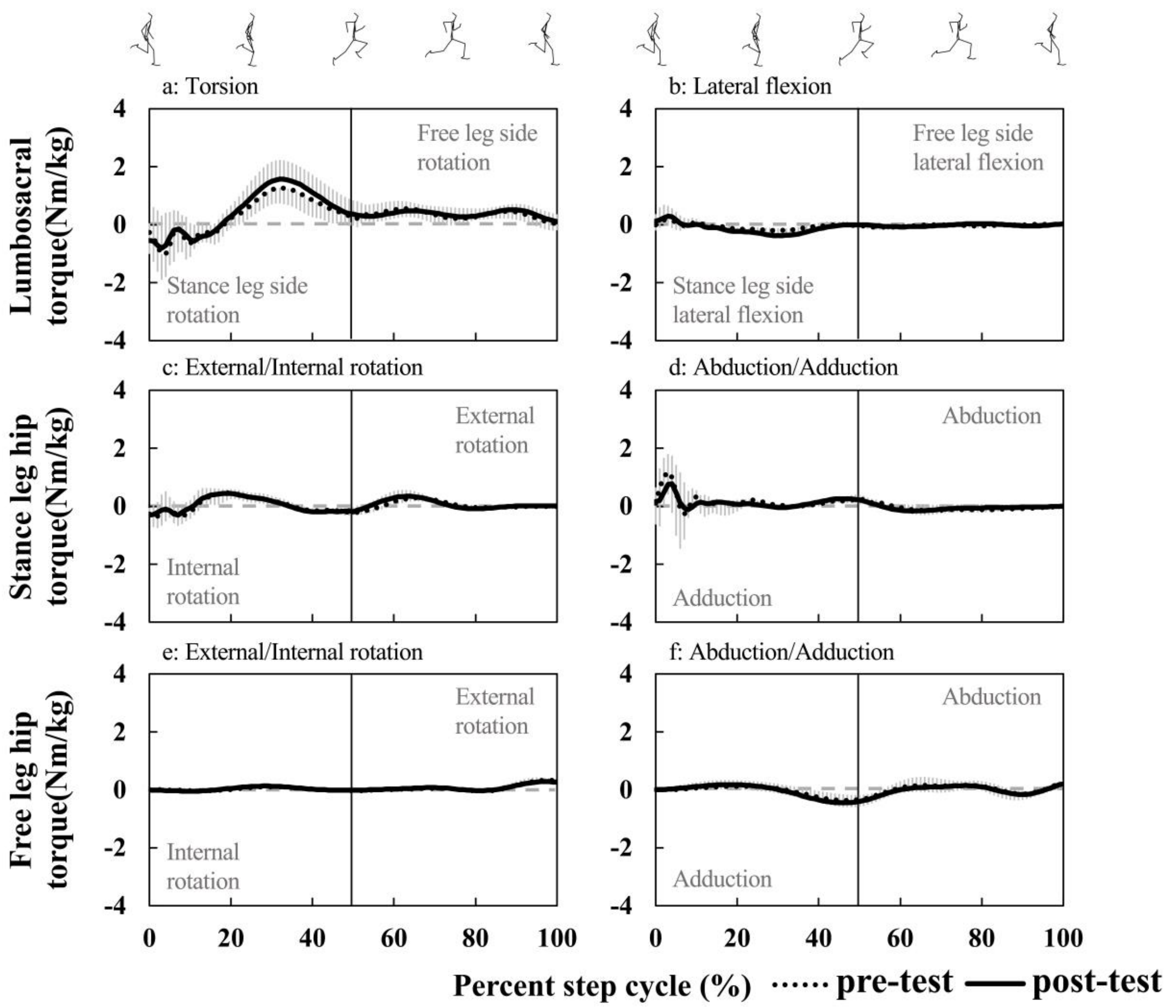
Figure 4 Ensemble averages with standard deviation of the individual components to pelvic elevation for the pre- test (dashed line) and the post-test (solid line).

DISCUSSION

The purpose of this study was to investigate the longitudinal changes in the kinematics and kinetics of the pelvis in response to increasing sprinting velocity. The study revealed that improving sprinting velocity during sprinting produced greater free leg side lumbosacral joint torsional torque during the stance phase, resulting in faster recovery of leg motion to increase the high step frequency.

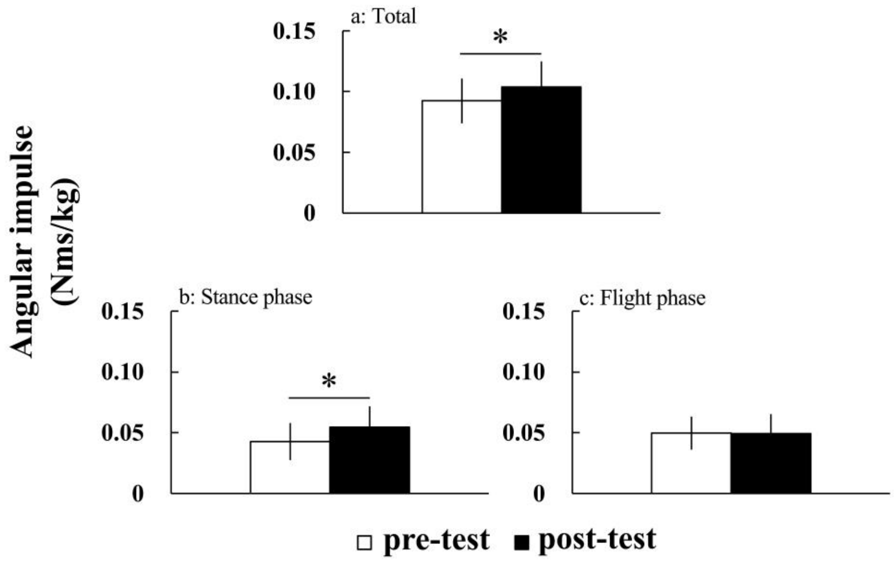
Longitudinal changes in sprinting velocity, step frequency, and step length

In this study, we first investigated sprinting velocity, step frequency, and step length to evaluate sprint performance. Although there was no significant difference in step length between the pre-test and the post-test, sprinting velocity and step frequency were significantly higher in the post-test than the pre-test (Table 1), suggesting that increasing step frequency during sprinting led to an improved sprinting velocity. Sprinting velocity is a key determinant of sprint performance (Bruggemann and Glad, 1990) and improving sprinting velocity is an important task. An inverse relationship exists between step frequency and step length (Hunter et al., 2004), and increasing both these variables is desirable. The relationships between sprinting velocity and step frequency or step length have been reported to be strongly correlated with step frequency (Ito et al., 2008) and step length (Hunter et al., 2004), however, the results are inconsistent. The improvement in step frequency and step length from the preparation phase to the competition phase is an important parameter in training plans (Mattes et al., 2014). Thus, determining whether step frequency and step length is more important for increasing sprinting velocity, from both a cross-sectional and longitudinal perspectives, presents a challenge. Therefore, each individual must increase their step frequency and step length according to the specific task requirements. Notably, step frequency is defined by contact time and flight time (Hay,1993; Hunter et al., 2004). Although there was no significant difference in contact time between the pre-test and the post-test, flight time was significantly shorter in the post-test than the pre-test (Table 1). Additionally, step length is affected by flight time (Hunter et al., 2004), and the flight time is determined by the vertical impulse. However, there was no significant difference in the vertical impulse between the pre-test and the post-test (Figure 1). Thus, the shortened flight time, which is important for the achieving step frequency and step length, may not be caused by the vertical impulse. Therefore, to improve sprinting speed during sprinting, the focus should be on reducing flight time by maintaining a large step length while achieving a higher step frequency, rather than attempting to improve both step frequency and step length.



Note. The vertical line is 50 % of the percent step cycle and represents the toe off instant for each test.

Figure 5 Ensemble averages with standard deviation of the individual components to pelvic rotation for the pre- test (dashed line) and the post-test (solid line).



*Note. *: p < .05.*

Figure 6 The integrated contributory components of the lumbosacral joint torsion angular impulse during the total, stance, and flight phase in the pre-test and post-test.

Longitudinal changes in pelvic and thigh movements and force exertion characteristics

We investigated the pelvic and thigh movements and force exertion characteristics contributing to achieving a high step frequency by shortening the flight time, thereby improving sprint performance. The thigh angle of the stance leg at STO and FTD were significantly smaller in the post-test than in the pre-test (Figure 3a, Table 3). The thigh angle of the free leg at STD and STO were significantly smaller in the post-test than in the pre-test (Figure 3b, Table 3), suggesting that the backward movement of the leg was smaller and the forward recovery movement was faster. An improvement in the recovery of leg motion during sprinting results in an improvement in step frequency (Chapman and Caldwell, 1983). The pelvis is connected to the spinal column at the centre of the torso via the lumbosacral joint and to the left and right legs via the hip joints, and the forward recovery movement of the legs is associated with the pelvis (Nagano et al., 2014; Sado et al., 2017). The pelvic anterior/posterior tilt angle at STD, STO, and FTD were significantly smaller in the post-test than the pre-test (Figure 2a, Table 2). Anterior pelvic tilt during the stance phase increases stance length by allowing the stance leg, which has a limited range of motion, to move more posteriorly (Franz et al., 2009; Nagano et al., 2014). Thus, preventing excessive forward tilt of the pelvis during the stance phase may prevent the thigh of the stance leg from remaining backward during the flight phase, promoting faster forward leg recovery.

The kinematic pattern of pelvic rotation indicated that the pelvis rotated backward toward the stance leg side, and that the maximum backward rotation toward the stance leg side occurred in the middle of the stance phase, along with forward rotation toward the free leg side after this point (Figure 2c). The kinetic pattern of pelvic rotation indicated that the lumbosacral joint torsional torque toward the stance leg side was greater until the middle of the stance phase, and that the lumbosacral joint torsion torque toward the free leg side was greater after this point (Figure 5a). These findings suggested that the pelvis on the stance leg side rotated forward by exerting a large lumbosacral joint torsional torque on the free leg side from the middle of the stance phase. The hip joint force on the stance leg increases the forward force to pull the stance leg forward (Author., 2022; Sado et al., 2017), whereas the joint force on the pelvis of the stance leg attempts to pull the leg backward during the stance phase. Consequently, the pelvic forward rotation toward the free leg side from the middle of the stance phase can primarily be attributed to the lumbosacral joint torsional torque toward the free leg side. The integrated contributory component of the lumbosacral joint torsion angular impulse during the total and stance phase were significantly greater in the post-test than the pre-test (Figure 6a, b). Thus, the greater lumbosacral joint torsion torque toward the free leg side from the middle of the stance phase to toe-off may increase the forward acceleration of the hip joint of the stance leg during the post-test. The free leg side lumbosacral joint torsional torque supported the forward recovery of leg motion after toe-off[7]. Therefore, achieving a high sprinting speed involves exerting free leg side lumbosacral joint torsional torque from the middle of the stance phase to toe-off, resulting in the faster recovery leg motion and increasing step frequency.

CONCLUSIONS

This study revealed that improving sprinting speed during sprinting produces greater free leg side lumbosacral joint torsional torque during the stance phase and assists the recovery of leg motion, resulting in a high step frequency.

AUTHOR CONTRIBUTIONS

Research design, data collection, data analysis, and text writing: Ota, K., Yoshida, T., Furuhashi, Y., Muratomi, K. Results analysis and text writing: Ota, K., Maemura, H., Tanigawa, S. Text revision and translation: Ota, Kazuki., Tanigawa, S.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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