Original Article

Trunk rotation enhances movement of the knee abduction angle while running among female collegiate middle- and long-distance runners

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ABSTRACT

This cohort study aimed to i) clarify the relationship between abduction of the knee joint and trunk motion during running in the stance phase, and ii) clarify the relationship between abduction of the knee joint during running in the stance phase and the amount of trunk rotation measured in a static position. Twenty-nine female collegiate middle- and long-distance runners participated. The knee abduction angle and absolute angles to the floor were calculated using a three-dimensional motion analysis device. Static trunk rotation was calculated. Trunk rotation angle to the supporting side ($r = 0.525$), thigh posterior tilt angle ($r = -0.510$), thigh adduction angle ($r = 0.417$), lower leg anterior tilt angle ($r = -0.483$), and static trunk rotation to the supporting side ($r = -0.429$) were significantly correlated with knee abduction angle. Trunk rotation angle to the supporting side (ß = 0. 465), thigh adduction angle (ß = 0.374), lower leg anterior tilt angle (ß = 0.228), and static trunk rotation to the supporting side (ß = -0.256) ($R^2 = .556$) were significantly correlated with the knee abduction angle. The increase or decrease in the knee abduction angle should consider the mutual influence of the lower limb and trunk motion.
Keywords: Knee joint; Middle- and long-distance running; Trunk function; Patellofemoral pain; Sports health.

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INTRODUCTION

Running is one of the most popular sports in Japan, both for female and male individuals. According to the Sasagawa Sports Foundation's "*Report on Sports Life*", the number of people who run at least once a year is estimated to be 9.64 million (Sasagawa Sports Foundation, 2018). Running causes large mechanical stress on the lower limb at contact with the floor (TS Keller et al., 1996). Continued running with poor form results in repetitive exposure to large mechanical stresses, resulting in running-related injuries (running injuries) (Phanpho and Rao, 2019; Moore et al., 2019; Roy and Cheung, 2011). The annual occurrence of running injuries has been reported to range from 19.4% to 79.3% (van Gent et al., 2007). Therefore, it is estimated that the occurrence of running injuries is high. Although most running injuries are related to the knee area (van Gent et al., 2007), patellofemoral pain (PFP) has been recognized as one of the most common causes of pain around the knee (Neal et al., 2016). PFP is not only common in runners, but also in athletes. A study of injury occurrence in long-distance athletes showed that PFP is one of the most likely injuries to occur in young long-distance athletes (Tenforde et al., 2011). Symptoms of PFP often become chronic, and as a result, the performance of those with PFP is expected to worsen. Furthermore, chronic PFP symptoms have been suggested to increase the risk of progression to osteoarthritis of the knee (van Gent et al., 2007; Thomas et al., 2010). Therefore, examining clinical evaluations related to PFP in young long-distance athletes may help to preserve athletic performance and help to prevent future osteoarthritis of the knee.

Previous reports (Dierks et al., 2008; Wilson and Davis, 2008; Wilson and Davis 2009; Besier et al., 2008; Lee et al., 2001; Salsich and Long-Rossi, 2010) have shown an association between PFP and hip and knee motion while running. Excessive adduction and internal rotation of the hip joint has been characterized in runners with a history of PFP (Dierks et al., 2008; Wilson and Davis, 2008; Wilson and Davis, 2009). These movements increase the abduction motion of the knee joint and increase the mechanical stress on the lateral aspect of the patellofemoral joint, which is considered a risk factor for the onset of PFP (Besier et al., 2008; Lee et al., 2001; Salsich and Long-Rossi, 2010). Recently, it has been reported that the mechanical stress on the knee joint increases as trunk displacement increases during movement, and trunk function has been focused on as a factor involved in the abduction movement of the knee joint (Houck et al., 2006). Since the location of the body's centre of mass is greatly influenced by the mass of the trunk, trunk movement can determine the direction of the floor reaction force vector and consequently affect the moment acting on the knee joint. Powers (Powers, 2010) suggested that when the centre of mass is shifted excessively toward the supporting side in a one-legged jump-landing motion, the floor reaction force vector shifts outward from the centre of the knee joint and an external abduction moment is generated at the knee joint. Furthermore, the pattern of combining these centre-of-mass translations with abduction movements of the knee joint is most likely to generate external abduction moments at the knee joint (Powers, 2010). Decreased trunk control during movement may increase the mechanical load on the knee joint by affecting lower limb control (Bendjaballah et al., 1997; Hewett et al., 2005a; Hewett et al., 2005b), and it has been reported to be a risk factor for the development of knee injury (Zazulak et al., 2007).

These results suggest that the characteristics of trunk movement related to the movement of knee abduction in the stance phase while running were extracted. The relationship between the abduction motion of the knee joint and trunk motion has been reported so far (Houck et al., 2006; Hewett et al., 2009), but these relationships have not been investigated while running. Clarification of these relationships while running will provide basic data for the evaluation of running injuries caused by PFP.

In clinical practice, we experience excessive trunk rotation in patients while running during the stance phase, which coincides with the excessive abduction motion of the knee joint that occurs immediately after ground contact. This dynamic alignment is expressed as an abnormal alignment (corkscrewing) (Kibler et al., 2006), which includes the movement of adduction and internal rotation of the thighs under one-leg load and an excessive element of rotation of the trunk to the supporting side. The movement of the trunk and lower limbs during stance phase while running is counter-rotated with the pelvis as the pivot point (Novacheck, 1998). Therefore, excessive abduction movements of the knee joint, including adduction and internal rotation movements of the thighs, could result in excessive rotational movements to the supporting side. Our first hypothesis was that there would be a positive correlation between the abduction motion of the knee joint and the rotational movement of trunk to the supporting side during stance phase while running. Additionally, the rotational movement of the trunk during the running stance phase may be influenced by the rotational mobility of the trunk, and this mobility function was expected to be related to the abduction movement of the knee joint. Therefore, as a second hypothesis, we predicted that the abduction movement of the knee joint during the running stance phase would be positively correlated with the amount of trunk rotation measured in a static position.

This study aimed to i) clarify the relationship between abduction of the knee joint and trunk motion during running in the stance phase, and ii) clarify the relationship between abduction of the knee joint during running in the stance phase and the amount of trunk rotation measured in a static position.

MATERIAL AND METHODS

Participants

The study subjects were 29 female collegiate middle- and long-distance athletes who were members of a track and field team during 2017-2019. PFP is twice as common in female athletes as in male athletes, indicating a sex difference in the frequency of occurrence (Boling et al., 2010). Therefore, all of the study subjects were restricted to women. At the time of the measurements, all of the subjects were able to perform the competition to the best of their abilities.

Measures

The measurements were performed in an indoor measuring room, and the floor reaction force meter was placed on a 20-meter straight track. A three-dimensional (3D) motion analyser (10 cameras, 200 Hz; Coretex 6, Motion Analysis, Santa Rose, CA, USA) and a floor reaction force meter (two pieces, 1000 Hz; TF-460, Tech, Uji City, Japan) were used as the measuring instruments. The reflective markers were 14 mm in diameter. Thirty-three markers were placed on the top of the head, front of the head, back of the head, seventh cervical vertebrae, tenth thoracic vertebrae, sternum, xiphoid process, right and left acromia, right scapulae, right and left elbows, right and left wrists, right and left superior anterior iliac spines, right and left superior posterior iliac spines, sacrum, right and left thighs, right and left lateral knees, right and left medial knees, right and left shanks, right and left lateral ankles, right and left medial ankles, shoe surfaces with the left and right heels projected, and shoe surfaces with the left and right toes projected.

Procedure

Running task

The running task was set as a running motion with the subject's shoes on in the measurement room. The subject continued to run through the measurement room in the same direction to the left, allowing the left foot to pass naturally over the floor reaction force with full ground contact. A running speed of 3.5 m/s was used as a target, and the subjects were allowed to practice beforehand. The ground contact pattern during the running motion was visually confirmed, and all subjects had heel contact. The measurements were repeated until data were obtained for one execution in which the left foot could be placed naturally on the floor reaction force.

Data collection

The data obtained by 3D motion analyser were processed by using the data analysis software Visual3D (C-Motion, Inc., Germantown, MD, USA). The 3D coordinates and force plate data were low-pass filtered at 10 Hz and 50 Hz, respectively (Williams et al., 2008). The segments of each body segment were defined by several points as follows: trunk segment (seventh cervical vertebrae, tenth thoracic vertebrae, sternal manubrium, and xiphoid process), pelvic segment (right and left superior anterior iliac bones, spine, and right and left superior posterior iliac spines), thigh segment (centre of the hip, lateral thigh, and centre of the knee), lower leg segments (centre of the knee, lateral leg, and centre of the ankle), and foot segments (centre of the ankle, heel, and toe). The calculation parameters were defined as the relative angle of the lower leg segment to the thigh segment (knee angle). Additionally, the trunk segment (trunk angle), pelvic segment (pelvic angle), thigh segment (thigh angle), lower leg segment (lower leg angle), and foot segment (foot angle) were calculated as absolute angles to the floor. The knee angle was calculated as the abduction angle in the frontal plane. The trunk and pelvic angles were calculated in the sagittal, frontal, and horizontal planes. The thigh angle, lower leg angle, and foot angle were calculated in the sagittal and frontal planes. The amounts of left and right trunk rotation were measured in a static position (static trunk rotation). The subject was placed in the side-lying position with arms crossed and upper shoulders automatically rotated backward to the maximum extent possible. The left side was defined as the supporting side. The vertical distance from the acromion to the floor was also measured in this position. Two examiners took the measurements: one examiner fixed the subject's pelvis so that it did not rotate and the other measured the vertical distance. The smaller this value, the greater the amount of trunk rotation.

Ethics statements

Subjects were informed orally and in writing of the priority of their protection and rights, freedom to participate or discontinue, purposes of the study, and effects on their health, and only those who gave their consent were included in the study. This study was approved by the local ethics committee (approval number: 6N170006).

Analysis

The abduction angle of the knee joint and angle of each segment were extracted from the values at the point of time when the floor reaction force backward component force maximum was reached. From the values, the angular values at the reference limb position proposed by McIlroy and Maki (McIlroy and Maki, 1997) were differentially extracted. Baur et al. (Baur et al., 2004) defined the running braking period as the point at which the floor reaction force switches from backward to forward component force. The point of maximum backward force component of floor reaction force while running is considered to be the point of maximum braking against forward propulsion. Since PFP may be caused by an increase in the mechanical stress on the patellofemoral joint (Besier et al., 2008; Lee et al., 2001; Salsich and Long-Rossi, 2010), we focused on the value at the time of maximum floor reaction force backward-component force.

Pearson's correlation coefficients (r) were obtained for the abduction angle of the knee joint and angles of each segment (trunk, pelvis, thigh, lower leg, and foot), and for data of static trunk rotation. Then, multi-regression analysis was performed using the stepwise method, with the abduction angle of the knee joint as the dependent variable and the variables that were significantly related by correlation analysis as factors. Statistical analysis was performed using SPSS Statistics version 25 (IBM Corp., Armonk, NY, USA), and p values < .05 were considered statistically significant.

RESULTS

Table 1. Results of each segment angle while running and the amount of static trunk rotation (n = 29), mean ± standard deviation.

Parameter	Value
Abduction of the knee joint angle (°)	0.2 ± 6.0
Trunk anterior tilt angle (°)	3.5 ± 2.6
Trunk flexion angle to the supporting side (°)	2.2 ± 2.2
Trunk rotation angle to the supporting side (°)	9.4 ± 6.6
Pelvic anterior tilt angle (°)	9.6 ± 6.6
Supportive downward pelvic tilt angle (°)	-3.1 ± 2.2
Pelvic rotation angle to the supporting side (°)	7.4 ± 5.2
Thigh posterior tilt angle (°)	24.5 ± 3.9
Thigh adduction angle (°)	4.1 ± 2.5
Lower leg anterior tilt angle (°)	15.9 ± 3.4
Lower leg lateral tilt angle (°)	6.1 ± 3.0
Foot dorsal flexion angle (°)	-1.4 ± 2.3
Foot eversion angle (°)	8.0 ± 9.8
Amount of static trunk rotation to the supporting side (cm)	14.9 ± 4.1
Amount of static trunk rotation to the non-supporting side (cm)	14.4 ± 4.8

Note. Data of the trunk, pelvis, and left lower extremity were calculated during the left stance phase.
The abduction angle of the knee joint and angle of each segment in this study were extracted from the values at the point of time when the floor reaction force backward component force maximum was reached. From the values, the angular values at the reference limb position were differentially extracted.
The amount of static trunk rotation was measured in a static position.
Running speed: 3.4 ± 0.2 (m/s)

Table 2. Correlations of the abduction angle of the knee joint with trunk, pelvic, and lower limb angles and the amount of static trunk rotation (n = 29), mean ± standard deviation.

Parameter	Correlation coefficient (r)	*p*-value
Trunk anterior tilt angle	-0.128	n.s.
Trunk flexion angle to the supporting side	-0.109	n.s.
Trunk rotation angle to the supporting side	0,525	**.003
Pelvic anterior tilt angle	-0.035	n.s.
Supportive downward pelvic tilt angle	-0,109	n.s.
Pelvic rotation angle to the supporting side	-0.186	n.s.
Thigh posterior tilt angle	-0.510	**.005
Thigh adduction angle	0,417	*.025
Lower leg anterior tilt angle	-0.483	**.008
Lower leg lateral tilt angle	-0.014	n.s.
Foot dorsal flexion angle	-0.259	n.s.
Foot eversion angle	0,105	n.s.
Amount of trunk rotation to the supporting side	-0.429	*.020
Amount of trunk rotation to the non-supporting side	-0.348	n.s.

*Note. n.s.: not significant, **: $p < .01$, *: $p < .05$.*
Data of the trunk, pelvis, and left lower extremity were calculated during the left stance phase.

Table 3. Results of multiple regression analysis with the abduction angle of the knee joint as a dependent variable.

Explanatory variable	Partial regression coefficient	Standard partial regression coefficient
Invariable	-8.658	
Trunk rotation angle to the supporting side	0.423	0.465
Thigh adduction angle	0.905	0.374
Lower leg anterior tilt angle	-0.396	-0.228
Amount of static trunk rotation to the supporting side	-0.369	-0.256

Note: Adjusted R-square = .556.

The mean (standard deviation) of subjects' age, height, weight, and career duration were 20.0 (1.4) years, 157.5 (5.9) cm, 47.2 (4.9) kg, and 9.7 (2.1) years, respectively. Table 1 shows each segment angle while running and the static trunk rotation. Table 2 shows the correlations between the abduction angle of the knee joint and angle of each segment and static trunk rotation. The abduction angle of the knee joint was significantly correlated with the trunk rotation angle to the supporting side (r = 0.525, $p < .01$), thigh posterior tilt angle (r = -0.510, $p < .01$), thigh adduction angle (r = 0.417, $p < .05$), lower leg anterior tilt angle (r = -0.483, $p < .01$), and static trunk rotation to the supporting side (r = -0.429, $p < .05$). No other statistically significant correlations were observed. Table 3 shows results of the multiple regression analysis with the abduction angle of the knee joint as the dependent variable. The abduction angle of the knee joint was significantly associated with the trunk rotation angle to the supporting side (standard partial regression coefficient, ß = 0 .465), thigh adduction angle (ß = 0.374), lower leg anterior tilt angle (ß = -0.228), and static trunk rotation to the supporting side (ß = -0.256). The adjusted R-square (R^2) was .556.

DISCUSSION

This study aimed to i) clarify the relationship between abduction of the knee joint and trunk motion during running in the stance phase, and ii) clarify the relationship between abduction of the knee joint during running in the stance phase and the amount of trunk rotation measured in a static position. The results showed a positive correlation between the knee joint abduction angle and trunk rotation angle to the supporting side, and a negative correlation between the knee joint abduction angle and static trunk rotation to the supporting side. These results support our hypotheses that the increase in abduction angle of the knee joint could be interpreted as being related to an increase in the trunk rotation angle to the supporting side and an increase in static trunk rotation to the supporting side.

Trunk rotation

Since the trunk and the lower limbs are anatomically connected, movement of the trunk may interact with movement of the lower limbs. Some researchers have reported that there is a relationship between abduction of the knee joint and lateral flexion of the trunk to the supporting side in one-legged jump landing movements, but the results of these studies were not consistent with this (Houck et al., 2006; Hewett et al., 2009). Some researchers analysed trunk rotation during running and stated that the upper trunk and lower trunk, including the pelvis, counter-rotate during gait movement, causing the upper trunk and lower trunk, including the pelvis, to cancel each other out and maintain the trunk's internal angular momentum from losing balance (Novacheck, 1998; Slocum and James, 1968; Hinrichs, 1987). It was considered that running motion requires rotation of the upper torso to maintain balance, and the trunk rotations that reflected this theory were extracted in this study. Additionally, based on the theory that excessive abduction motion of the knee joint caused by adduction/internal rotation of the thighs and movement of trunk rotation to the supporting side effect each other (Kibler et al., 2006), it is thought that the increase in abduction of the knee joint during the running stance phase may be related to the maintenance of balance by increasing the angle of trunk rotation to the supporting side. This study's results quantify these relationships.

Here, the increase in the abduction angle of the knee joint was associated with an increase in static trunk rotation to the supporting side. During running motion, the trunk and lower limbs are in reverse rotation with the pelvis as the pivot point (Novacheck, 1998). Although the excess or under-abundance of trunk rotation was not discussed here, it was considered that trunk mobility to the supporting side may contribute to the adjustment of the trunk rotation angle while running, and movement of abduction of the knee joint may occur as a result of the interaction with trunk rotation. The results suggested that an increase in the abduction angle of the knee joint is associated with an increase in static trunk rotation to the supporting side.

Lower limbs

Our study revealed a positive correlation between the abduction angle of the knee joint and thigh adduction angle. Huberti and Hayes (Huberti and Hayes, 1984) showed that an increase in the abduction angle of the knee joint was associated with an increase in the quadriceps angle. Our study's results showed no significant association between the abduction angle of the knee joint and lower leg angle in the frontal plane. Therefore, changes in the adduction angle of the thigh led to changes in the quadriceps angle, and a positive correlation between the abduction angle of the knee joint and thigh adduction angle was expected to occur. This would have been consistent with the results reported by Huberti and Hayes (Huberti and Hayes, 1984).

Our study also showed no significant relationship between the abduction angle of the knee joint and pelvic angle in the frontal plane. Increased non-supportive downward pelvic tilt has been reported to be associated with an increased abduction angle of the knee joint (Takacs and Hunt, 2012), but this study's results were not consistent. In the analysis of one-legged squatting movements, it was reported that the increase in the downward tilt of the pelvis on the non-supporting side produced a pattern of abduction of the knee joint, and the abduction of the thighs produced a pattern of abduction of the knee joint (Kagaya et al., 2015). In our study, there was a positive correlation between the increase in the abduction angle of the knee joint and increase in the thigh adduction angle, suggesting that the running movements of these subjects tended to be more of a pattern of abduction movements of the knee joint as a result of adduction of the thigh. Therefore, the results did not seem to show a significant relationship between the abduction angle of the knee joint and pelvic angle in the frontal plane.

There were negative correlations of the abduction angle of the knee joint with the thigh posterior tilt angle and lower anterior tilt angle. The relative angle between the thigh and the lower leg represents the knee joint angle, and this study's results may be comparable to the relationship between the abduction angle of the knee joint and flexion angle of the knee joint. During the braking phase of running, flexion of the knee joint acts as a shock absorber and causes eccentric contraction of the knee extensor muscles (Novacheck, 1998). External knee flexion moment increases when a large load is placed on the supported lower limb, and the knee flexion angle tends to increase (Novacheck, 1998). Although this study did not analyse this aspect, it is thought that if there is a decrease in knee joint extensor strength, the knee joint flexion angle would be reduced during the braking phase of the running motion. Additionally, a decrease in hip abduction strength is associated with an increase in the abduction angle of the knee joint (Claiborne et al., 2006). These results suggest that the relationships of the abduction angle of the knee joint with the thigh posterior tilt angle and lower limb anterior tilt angle in this study were appropriate.

The trunk rotation angle to the supporting side, thigh adduction angle, lower leg anterior tilt angle, and static trunk rotation to the supporting side were selected as the explanatory variables for the knee joint abduction angle. The adjusted R^2 value indicated that the accuracy of the multiple regression equation was moderately good. A modified approach to selected lower limb and trunk movements may be required to reduce the abduction angle of the knee joint, and this may provide basic data to evaluate running injuries in PFP.

The limitations of this study are as follows. First, this study had a small number of subjects, limiting statistical interpretation. Second, the results were obtained from only female middle- and long-distance athletes from a single university. In the future, a multi-institutional investigation is required. Lastly, the morphological characteristics of the subjects were not examined. Powers (Powers, 2003) stated that increased foot pronation increases internal rotation of the lower leg, which in turn increases the abduction angle of the knee joint. The pronation of the foot during loading movement has been shown to be involved in lowering the medial longitudinal arch (Cornwall et al., 1995). These findings suggest that the morphological characteristics of the foot should be considered in changes in the abduction angle of the knee joint.

CONCLUSIONS

During the running stance phase, there were relationships between the increased abduction angle of the knee joint and increased trunk rotation angle to the supporting side, and between the increased abduction angle of the knee joint and increased static trunk rotation to the supporting side. Increasing or decreasing the abduction angle of the knee joint requires consideration of the interaction between the lower extremity and trunk movements, suggesting that this study provides basic data for evaluating running injuries in PFP.

AUTHOR CONTRIBUTIONS

YK carried out the sports injury studies, participated in the motion analysis, and drafted the manuscript; MT and TM carried out the running measurements and performed the statistical analysis; HO, DF, and HK conceived of the study, participated in its design and coordination, and helped to draft the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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DISCLOSURE STATEMENT

All research protocols adhered to the tenets set by the Declaration of Helsinki and the current laws of the country in which the research was performed.

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