

Research article

Bilateral ground reaction forces and joint moments for lateral sidestepping and crossover stepping tasks

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Abstract

Racquet sports have high levels of joint injuries suggesting the joint loads during play may be excessive. Sports such as badminton employ lateral sidestepping (SS) and crossover stepping (XS) movements which so far have not been described in terms of biomechanics. This study examined bilateral ground reaction forces and three dimensional joint kinetics for both these gaits in order to determine the demands of the movements on the leading and trailing limb and predict the contribution of these movements to the occurrence of overuse injury of the lower limbs. A force platform and motion-analysis system were used to record ground reaction forces and track marker trajectories of 9 experienced male badminton players performing lateral SS, XS and forward running tasks at a controlled speed of 3 m·s⁻¹ using their normal technique. Ground reaction force and kinetic data for the hip, knee and ankle were analyzed, averaged across the group and the biomechanical variables compared. In all cases the ground reaction forces and joint moments were less than those experienced during moderate running suggesting that in normal play SS and XS gaits do not lead to high forces that could contribute to increased injury risk. Ground reaction forces during SS and XS do not appear to contribute to the development of overuse injury. The distinct roles of the leading and trailing limb, acting as a generator of vertical force and shock absorber respectively, during the SS and XS may however contribute to the development of muscular imbalances which may ultimately contribute to the development of overuse injury. However it is still possible that faulty use of these gaits might lead to high loads and this should be the subject of future work.

Key words: Badminton, movement, biomechanics, injury.

Introduction

Overuse injury of the lower limb is the dominant risk factor of competitive badminton. While injury frequencies in relation to exposure time are comparable with sports such as tennis and volleyball (Jørgensen and Hølmich, 1994) overuse injuries make up a much larger percentage of injuries compared to other racket sports, contributing to about ¾ of all injuries sustained in badminton (Caine et al., 1996, Jørgensen and Winge, 1987). The lower limb is a primary injury site (Caine et al., 1996) with a clear shift toward lower limb injury with increasing level of playing skill (Jørgensen and Winge, 1987) and particularly the foot, ankle and knee are recognized as common sites for the development of overuse as well as acute injuries including sprains, strains and tears (Hensley and Paup, 1979; Høy et al., 1994; Jørgensen and Winge, 1987; Moh-tadi and Poole, 1996).

Sidestepping (SS) and crossover stepping (XS) movements are frequently used in badminton and tennis as well as a number of other sports. The biomechanics of SS and XS cutting movements in sports such as basketball have received interest in the past due to the associated risk of non-contact knee ligament injury as a result of their use to evade an opposing player (Besier et al., 2001a; 2001b; Cross et al., 1989; Dayakidis and Boudolos, 2006; Dempsey et al., 2007; Houck and Yack, 2003; Houck et al., 2006; Mclean et al., 2004; 2005). However, in the absence of direct contact with the opposing player in badminton or tennis, the SS and XS movement is not performed in a cutting manner but rather as a planned movement to allow for linear motion toward the target (i.e. the shuttle-cock or the tennis ball). Use of the SS or XS allows the player to move toward the target quickly while facing the opposite court throughout and the movement task may consist of a number of successive steps.

According to Nigg (1985), mechanical loading can have both positive and negative effects on the musculoskeletal system. The biopositive effects include the strengthening of the musculoskeletal system, due to moderate overloading and adequate rest periods, while bi-negative effects, due to for example excessive loading, include structural damage of the musculoskeletal system, that may ultimately lead to injury. Despite this established concept of a cause and effect relationship of mechanical loading and injury and the interest in the relationship between biomechanical variables and overuse injuries, which include stress fractures, shin splints, tendonitis and fasciitis, the exact causes that lead to overuse injury have yet to be determined (Hreljac et al., 2000). In the current literature a variety of interacting causes including training, anatomical and biomechanical variables are thought to contribute to the development of overuse injury (Hutchinson and Ireland, 1995; Kader et al., 2002; Kvist, 1994; Nigg et al., 1995; Paavola et al., 2002). Particularly biomechanical factors have been the focus of studies trying to establish a causative relationship of motion and injury. Repetitive tissue microtrauma and overloading due to repetition of a specific action have been cited as causes for the development of overuse injury (Chard and Lachmann, 1987; Kader et al., 2002; Kvist, 1994). As a consequence, ground reaction forces during repetitive tasks, particularly running, have been studied and a number of aspects of force exposure have been highlighted as contributors to overuse injury development including the magnitude of impact forces (Nigg et al., 1981), the rate of

impact loading (Nigg, 1983) as well as the magnitude of the push-off force (Cavanagh and Lafortune, 1980). Furthermore, the magnitudes of loads at common injury sites and joint moments during running have been examined (Buczek and Cavanagh, 1990; Scott and Winter, 1990; Winter, 1983). These studies provide insight into the functional significance of the joints of the lower limbs to the running gaits, highlighting the contribution of the knee and ankle, and provide a framework for the cause and effect relationship between motion and injury by quantifying peak loads.

Therefore there are a number of factors which affect the development of musculoskeletal injury. It is clear that the assessment of biomechanical factors plays an important role in the treatment and prevention of injury in running. Racket sports such as badminton and tennis however do not rely solely on running for on-court locomotion but utilize alternative gait strategies including lateral SS and XS tasks. However, despite the apparent importance of these movements to the games there appears to be no information on the contribution of the leading and trailing limb to the gait cycle when performing linear SS and XS movements for a number of consecutive steps. Considering the comparatively large percentage of overuse injuries in badminton it appears essential to quantify the biomechanical demands of these movements in order to assess the consequences of their application in-game in comparison to alternative movements such as running and predict their contribution to the development of overuse injury.

The purpose of this study was therefore to investigate the biomechanics of a standardized lateral SS and XS maneuver in comparison to a running movement in the laboratory to assess the mechanical demands of these movements on the athlete. The aims were to firstly record bilateral ground reaction forces in order to compare and contrast force exposure during the stance phase of the movements. Secondly bilateral kinematic data was recorded for the calculation of hip, knee and ankle joint moments in order to quantify their magnitude and to identify the contribution of both the leading and trailing limb to the stance phases of the SS and XS gaits. Quantification of the mechanical demands will provide valuable insight into the mechanisms involved in lateral movements, as applied to the sport of badminton. Gaining specific insight into the biomechanics of these movements enhances our understanding of the role of sport-specific movements in the cause and effect relationship of motion and injury. Furthermore, it is hoped that the data will provide useful information on the possible advantages and disadvantages of gait use in badminton, which may benefit the athlete and coach in developing training methods and ultimately in preventing injury.

Methods

Subjects

Nine male student badminton players proficient in SS and XS movements, with no history of major lower limb injury, volunteered for participation in the study (mean age = 20.7 yr, height = 1.78 ± 0.05 m, weight = 73.2 ± 9.3 kg). Players were from the male students' 1st or 2nd team,

played at least 6 hours of badminton per week and regularly competed in University and national level competition. These players were selected to ensure they had sufficient skill in performing the required SS and XS tasks. All procedures were approved by the local ethics committee at Loughborough University and written informed consent was obtained from the participants before data collection.

Kinematics and force plate recordings

A two-camera, Cartesian Optoelectronic Dynamic Anthropometer (CODA, Charnwood Dynamics Ltd, UK) was used to record 3D bilateral kinematics for the lower limb using a specialized wand system supplied by Charnwood Dynamics Ltd. Marker positions were sampled at 200 Hz and the raw marker position data filtered at 10 Hz following recommendations by Winter (1990). The cameras were placed on opposite ends of a raised wooden walkway (8.5m x 1.2m), on which all movements were performed. A Kistler (Type 9286A) mobile multi-component forceplate, integrated into the middle of the walkway, was used to record ground reaction forces (GRFs). GRF data was sampled at a hardware limited frequency of 200Hz. A higher recording frequency was desirable but could not be implemented due to restrictions to the sampling frequency when simultaneously recording kinematic and force data within the software supplied by CODA. GRF onset and offset was determined from the vertical GRF with a cut-off value of 15N.

Kinetic data

Kinetic data was calculated from GRF and kinematic data using an inverse dynamics approach within the data capture and analysis software CODAmotion (V6.68) supplied by Charnwood Dynamics. The resultant data on moments and powers was exported to Microsoft Excel for further processing and analysis.

Experimental design

Data was collected during repeats of three movement tasks: a straight line Run, lateral sidestepping (SS) and lateral crossover stepping (XS). 10 successful repeats of each task were performed on the walkway at a controlled speed of 3.0 ± 0.3 m·s⁻¹. This speed was chosen to represent the top end of the preferred speed of locomotion for SS and XS by experienced male participants, based on a preliminary study. This speed furthermore allowed for comparisons of the gathered data with the biomechanics literature where 3 m·s⁻¹ was frequently chosen to represent a slow running speed. Speed of locomotion was controlled by a set of wireless light gaits (IRD-T175, Brower Timing Systems), aligned parallel to the wooden walkway and located at waist height around the centre of the forceplate. Markers and marker-wands were attached to the lower limb and the movement task order was randomly assigned to control for fatigue. SS and XS commenced with the participant in a slightly crouched, wide-stance position to the left of the forceplate. The participant then performed the movement to the right, hitting the force platform on the third stride with the leading limb, for leading limb recordings, and the trailing limb, for trailing limb recordings, and returned to the starting position to the left of the forceplate. Due to the larger stride length

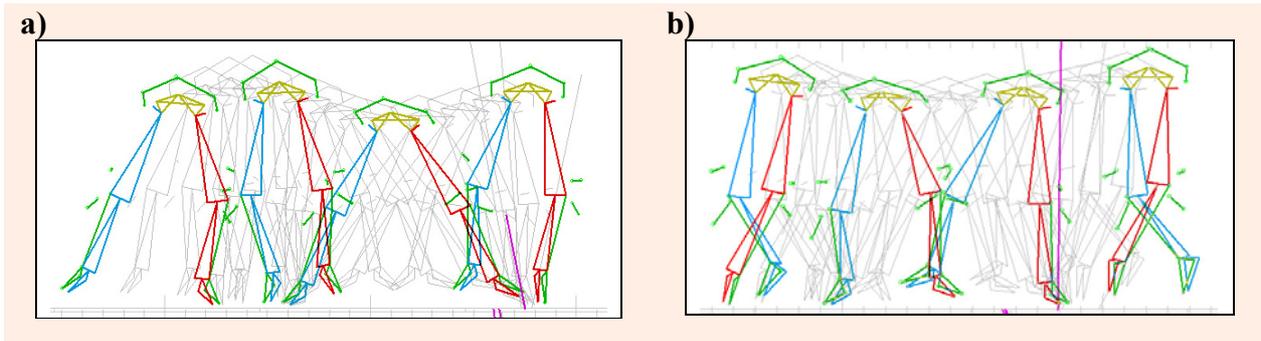


Figure 1. Posterior view of the (a) lateral sidestepping and (b) lateral crossover stepping movements tested. The leading limb is shown in red while the trailing limb is shown in blue. The yellow structure connecting the limbs represents the hip. The green lines indicate the wand system references used for motion capture. Images taken from CODAmotion software.

for running the participants hit the force plate on the second stride for the Run. As illustrated in Figure 1a, the SS consisted of a lateral movement in the direction of the leading limb (red). The XS Figure 1b consisted of movement of the trailing limb beyond the midline of the body while the leading limb performed the same movement as during the SS. Before recordings were taken, the participants were given as many practice runs as necessary to assure they felt comfortable with the movements, the process of data capture and the kinematic recording equipment attached to their lower extremities. Furthermore, this time was used to ensure the participants successfully and reliably achieved the required speed of locomotion and consistently hit of the centre of the force plate with their leading or trailing foot. Only trials within the required speed range of $3.0 \pm 0.3 \text{ m}\cdot\text{s}^{-1}$ were saved for data analysis.

A restriction of the current investigation was caused by the change in body alignment during the Run, compared to the SS and XS. This meant that complete marker sets for the kinematic data could not be recorded for the Run condition. However, since speed of locomotion for both the SS and XS as well as the Run condition was controlled using light gates and was not dependent on the kinematic data, direct comparison of ground reaction force measures of all three movement tasks could confi-

dently be performed in this investigation. However, the lack of complete kinematic marker sets for the Run condition restricted the statistical analysis of the net peak joint moments to a comparison of the leading and trailing limb during the SS and XS only. To compensate for the missing data depth, additional comparisons of the lateral gaits to walking and running joint kinetics will be performed with reference the relevant existing literature.

Statistical analysis

GRF and kinetic data for the three modes of transport was analyzed using a repeated measures test of variance (ANOVA) in the statistical analysis tool SPSS. Main effects were furthermore analyzed using pairwise comparisons. Statistical significance was taken as $p < 0.05$.

Results

Ground reaction force

Horizontal (F_z) and vertical (F_x) GRF averages for one participant are presented in Figure 2. Braking (F_{xb}) and push-off (F_{xp}) phases of the horizontal force curve are clearly visible.

Comparison of the effect of gait within the leading limb during the SS, XS and Run (Figure 3) indicates a

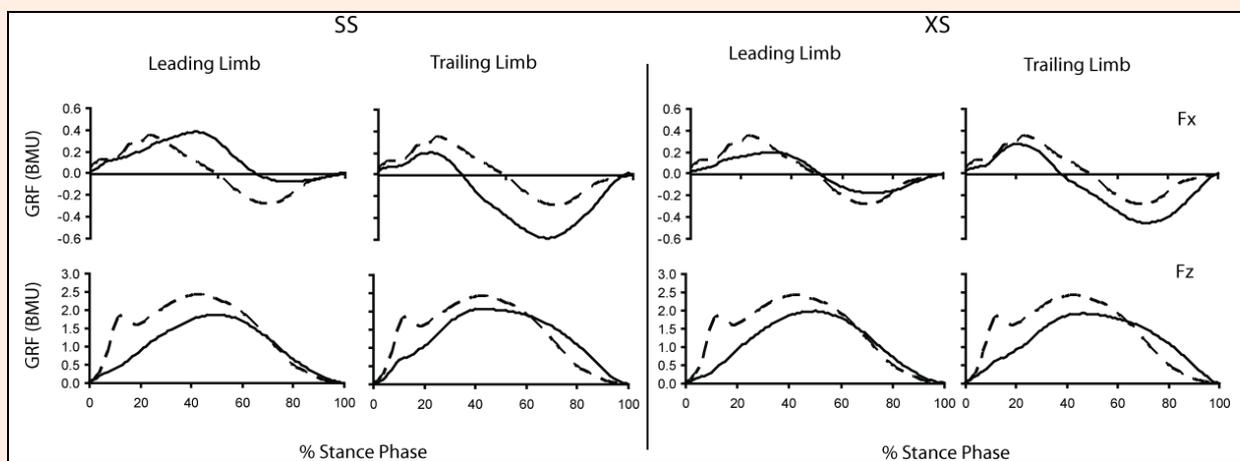


Figure 2. GRF data averages for a typical subject performing SS, XS and running (dashed line) gaits. The vertical scale is normalized to body mass units (BMU, where $1 = 1 \times$ body mass) and the horizontal scale is normalized to stance phase duration from impact to toe-off of the respective limb.

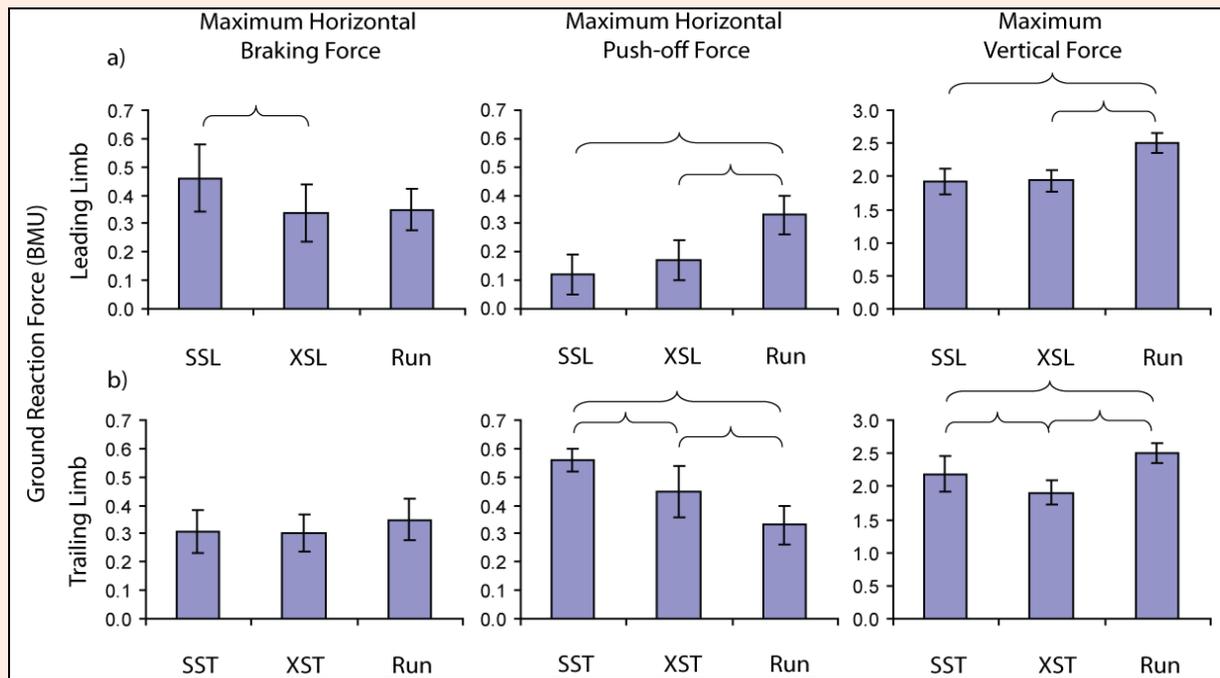


Figure 3. GRF averages for the 9 squad members is presented for the leading and trailing limb SS and XS as well as right limb Run. Data is presented for a) the leading limb and b) the trailing limb.

{ indicates statistically significant differences in vertical and horizontal GRF parameters.

significant effect on maximum F_z and F_{xp} ($p < 0.001$, $F = 45.216$ and $p < 0.001$, $F = 32.854$ respectively where $df = 2$) and a small but significant effect on maximum F_{xb} ($p < 0.05$, $F = 4.185$, $df = 2$). Further pairwise comparison showed that maximum F_z and F_{xp} were significantly larger in the Run compared to the SS ($p < 0.001$ for F_z and F_{xp} respectively) and XS ($p < 0.001$ for F_z and F_{xp} respectively) with no significant differences between SS and XS (F_z $p = 0.627$ and F_{xp} $p = 0.087$). Maximum F_{xb} was slightly larger in the SS than XS ($p < 0.05$) with no significant differences between the lateral gaits and running ($p = 0.06$ and $p = 0.741$ for the SS/Run and XS/Run respectively).

In the trailing limb gait had a significant effect on maximum F_z ($p < 0.001$, $F = 19.741$) and F_{xp} ($p < 0.001$, $F = 37.933$). There was no effect of gait on F_{xb} ($p = 0.31$, $F = 1.26$). Further pairwise comparison indicated a significantly larger maximum F_z in the Run than SS ($p < 0.05$) and XS ($p < 0.001$). SS caused a larger maximum F_z peak than the XS ($p < 0.01$). F_{xp} was significantly larger during the SS than XS ($p < 0.01$) and Run ($p < 0.001$) and XS displayed a larger maximum force peak than the Run ($p < 0.01$).

Differences were furthermore observed between the leading and trailing limbs. During the SS maximum F_z and F_{xp} were significantly larger in the trailing than the leading limb ($p < 0.05$ and $p < 0.001$ for F_z and F_{xp} respectively). No significant trend was identified for the maximum F_{xb} data for the SS ($p = 0.093$). In the XS the trailing limb displayed significantly larger F_{xp} ($p < 0.001$), however, no significant trends between the leading and trailing limbs were identified for maximum F_{xb} ($p = 0.375$) or maximum F_z ($p = 0.406$).

Joint moments

Joint moments at the hip, knee and ankle were similar between the SS and XS. Investigation of the effect of gait within the leading limb indicated a small but significantly larger peak knee extensor moment in the XS compared to the SS ($p < 0.05$). In the trailing limb the peak hip extensor moment was furthermore significantly larger in the SS than the XS ($p < 0.01$).

Differences between the leading and trailing limb during the SS and XS, summarized in Figure 4, were more pronounced. In both the SS and XS the trailing limb generated significantly larger hip abductor (SS $p < 0.001$ & XS $p < 0.01$), hip flexor (SS $p < 0.05$ & XS $p < 0.001$) and knee extensor (SS $p < 0.001$ & XS $p < 0.01$) moments. During both the SS and XS the leading limb developed significantly larger hip adductor (SS $p < 0.01$ & XS $p < 0.001$) and knee flexor (SS $p < 0.01$ & XS $p < 0.05$) moments and a larger hip extensor moment during the XS ($p = 0.01$). No significant differences were observed for the hip extensor moment in the SS ($p = 0.108$). No significant differences were observed at the ankle ($p = 0.294$ and $p = 0.332$ for plantarflexor moments; and $p = 0.072$ and $p = 0.545$ for dorsiflexor moments during the SS and XS respectively).

Comparison of the joint moments during SS and XS with the literature (Figure 5) for walking and running indicates that the joint moments are generally within the range expected for running. There appears to be a relatively high demand of the SS and XS on the hip abductors and extensors of the leading limb with a comparatively lower contribution of the knee and ankle joints. In the trailing limb there is a comparatively large hip abductor and flexor moment as well as a large knee extensor moment.

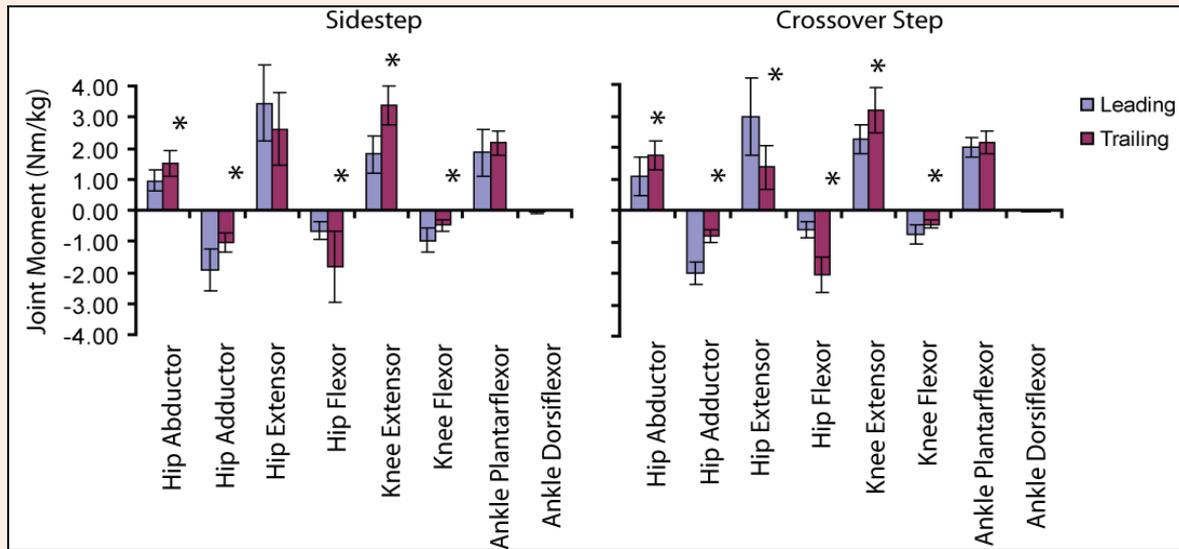


Figure 4. Summary of the differences in peak joint moments between the leading and trailing limbs during the SS and XS. * indicates significant differences between the leading and trailing limb. Joint moment values are expressed as $\text{Nm}\cdot\text{kg}^{-1}$.

Discussion

It was the aim of this investigation to record bilateral ground reaction forces and joint kinetics of lateral movement tasks in order to quantify their mechanical demands and the contribution of the limbs to the gaits. Data on the magnitude of the maximum force and peak joint moment parameters was compared to alternative movement strategies such as walking and running with a view to gaining specific insight into the biomechanics of these movements and thereby enhance our understanding of the role of sport-specific movements in the cause and effect relationship of motion and injury in badminton.

Ground reaction force

The results of the current investigation show that GRFs

for running were similar to those stated in the literature (Table 1). The vertical force traces for the SS and XS largely lacked the characteristic impact peak observed during the Run and reported for heel-toe running in the literature (Cavanagh and Lafortune, 1980; Hamill et al., 1983; Keller et al., 1996; Munro et al., 1987). In the current study all participants displayed impact peaks during the Run, while none displayed impact peaks at the trailing limb during the SS and XS. The underlying cause for this observation is likely due to the use of a forefoot landing approach by the trailing limb during the SS and XS which is in line with the observations by Cavanagh and Lafortune (1980) and Keller et al. (1996). A vertical impact peak was observed in a number of participants at leading limb contact with the ground (4 and 3 participants for the SS and XS respectively) which can be explained by their

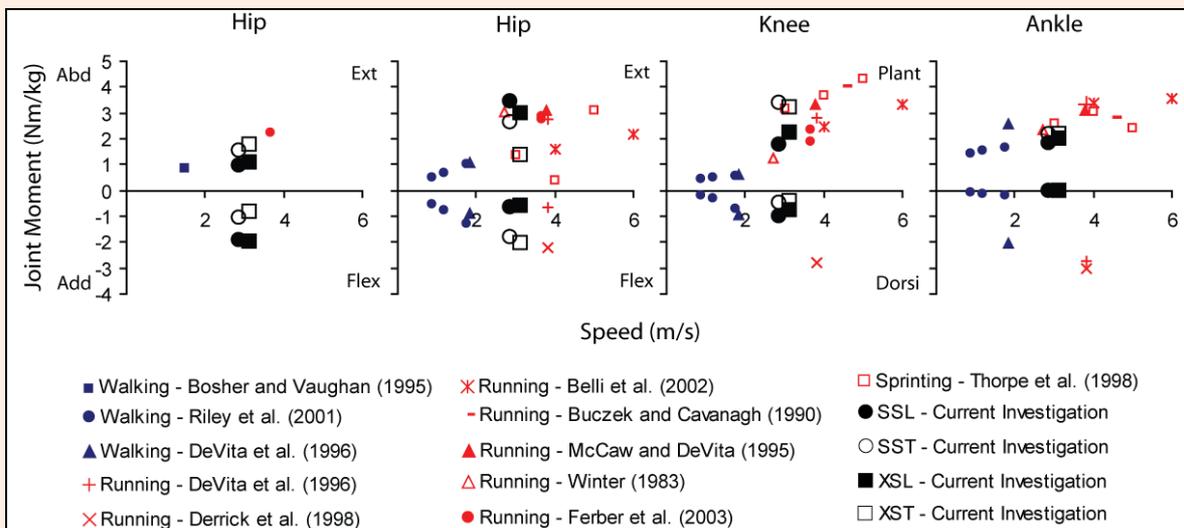


Figure 5. Joint moments from the current investigation compared to the literature. Joint moments are expressed as Newton meters per kg body mass. The horizontal scale is speed, expressed in meters per second.

Table 1. Literature summary of vertical and horizontal ground reaction force means for walking and running gaits with reference to the current investigation.

Author	Gait	Speed (m·s ⁻¹)	Vertical (BMU)	Horizontal Braking (BMU)	Horizontal Push-off (BMU)
Current Study	SSL	3	1.91	0.44	0.12
	SST	3	2.19	0.31	0.56
	XSL	3	1.92	0.32	0.16
	XST	3	1.91	0.35	0.45
	Run	3	2.50	0.35	0.33
Munro et al. (1987)	Run	3	2.51	0.15	0.14
		3.5	2.62	0.18	0.17
		4	2.72	0.21	0.20
Keller et al. (1996)	Jog	3	2.10	-	-
Hamill et al. (1983)	Run	4	2.79	0.49	0.37

use of a heelstrike. The majority of participants utilized a laterally rotated leading limb during the SS and XS which allowed for the heelstrike mechanism in some of the participants. Since early impact peaks were largely absent, this investigation focused on the maximum force magnitudes. With the exception of peak horizontal push-off force of the trailing limb the force maxima of vertical and horizontal forces during the SS and XS were significantly lower than those during running. It therefore appears that both peak force magnitude and peak vertical impact force can be discounted as injury causing factors in the lateral gaits. The force data would suggest that particularly the XS is of benefit to the participant for reducing the magnitude of vertical and horizontal force maxima.

Joint moments

The mean joint moment peaks for the leading and trailing limb during the SS and XS are within the expected range for running. As Figures 4 and 5 show there is a clearly visible difference in the contribution of the leading and trailing limb to the gait cycle. The trailing limb acts as the main shock absorber, as indicated by the large knee extensor and slightly larger ankle plantarflexor moment. Furthermore, the trailing limb stabilizes and transfers the centre of mass of the body during stance until weight acceptance by the leading limb. The leading limb in turn appears to be involved primarily in generating extensor moments at the hip, knee and ankle joints to generate the lift required for the aerial phase following toe-off. The mechanism of this is similar to that of a jump, with a relatively large contribution of the hip extensors and smaller contribution of the knee extensors and ankle plantarflexors, in line with observations by Stefanyshyn and Nigg (1998).

The distinct role of the leading and trailing limb during the lateral movement tasks suggests an asymmetrical contribution of the musculature. It may be argued that repeated use of the SS and XS movement tasks in the direction of one limb, as occurs frequently in badminton, where particularly the XS is performed in the direction of the dominant limb, may contribute to the development of muscular imbalances. Such imbalances have repeatedly been associated with increased risk of injury in athletes (Fowler and Reilly, 1993; Grace et al., 1984; Knapik et al., 1991). Differences in the proportions of the dominant (leading) and non-dominant (trailing) limb, as well as a low hamstring to quadriceps strength ratio in badminton

players have been reported by Mikkelsen (1979). For the lateral gaits, the apparent propulsive function of the leading limb and support function of the trailing limb and shift toward utilization of proximal muscle groups compared to walking or running may contribute to imbalances of the hip adductors/abductors and hip extensors. This may potentially alter the normal direction in which a tendon exerts force and thereby expose the athletes to an increased likelihood of overuse injury (Hess et al., 1989; Kannus, 1992; Witvrouw et al., 2000). However, other factors such as previous injury, which appears to have a lasting effect on hamstring and quadriceps muscle moment ratios (Dauty et al., 2003), or adaptive hypertrophy, such as those reported by Mikkelsen (1979) may be the underlying cause for muscular imbalances. The influence of the asymmetric contribution of the limbs in lateral gaits on the development of muscular imbalances therefore remains speculative.

Of course this study has only looked at correctly performed SS and XS gait and it is entirely possible that the forces and moments associated with incorrectly performed or abnormal gaits may be much higher. Furthermore, the selection of experienced male badminton players only may have influenced the magnitude of the observed forces. Therefore, the results should be regarded as typical for advanced players. Future work should seek to characterize such gaits perhaps using continuous monitoring via accelerometers in game situations to see whether there is any indication of high forces in these situations.

Conclusion

Contrary to expectations the lateral SS and XS movements display a number of characteristics that are of potential benefit to the participant in terms of the risk of overuse injury. Ground reaction forces were generally lower and largely lack a vertical impact peak which appears to indicate a reduced risk of overuse injury for the athlete compared to heel-toe running. The moments generated during the lateral stepping movement tasks are within the limits of running. However moments do show an asymmetric contribution of the leading and trailing limbs as well as a larger contribution of the proximal joints to the generation of extensor moments in the leading limb. Based on this data the use of the SS and XS may be recommended due to the apparent reduction of maximum vertical reaction force.

Acknowledgments

The authors would like to thank Olivia Northover for assistance in data collection and the Loughborough University Students Badminton Club for their participation in the study.

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Key points

- Ground reaction forces and joint moments during lateral stepping are smaller in magnitude than those experienced during moderate running.
- Force exposure in SS and XS gaits in normal play does not appear to contribute to the development of overuse injury
- The leading and trailing limbs perform distinct roles, acting as a generator of vertical force and shock absorber respectively.
- This distinct contribution may contribute to the development of muscular imbalances which may ultimately contribute to the development of overuse injury.

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