BWF Sports Science Research Project 2018-2019

Final report

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Title: Investigation of knee joint loadings from lunges among Chinese elite badminton athletes: a subject-specific musculoskeletal and finite element analysis

Area: Biomechanics / Sports Medicine & Injuries

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Project summary:

This project investigated the knee joint kinematics, kinetics and contact forces during Right-Forward, Right-Backward, Left-Backward and Left-Forward lunges among Chinese athletes via a musculoskeletal modelling and finite element simulation approach.

Key findings indicated that the knee motions of the adduction/abduction and internal/external rotation were significantly different especially during the Left-Backward lunges. Additional higher patellofemoral joint contact force and cartilage stress loading were found in the Left-Backward and Left-Forward lunges, which may link to knee pain.

Greater knee flexion moment was found during Right-Forward lunges, following with larger extension moment in Left-Backward lunges during the weight-acceptance phase. The Right-Backward lunges presented greater adduction moment. These should also be noted as potential factors contributing to overuse injury risks.

The Left-Backward and Left-Forward lunges also exhibited greater total knee contact force, while Right-Forward lunge had larger contact force in the medial compartment of knee joint. Left-Backward and Left-Forward lunges showed larger contact force in the lateral compartment of knee joint. Quadriceps muscle force contributions were revealed that could assist the training program for developing these muscles, so as to prevent potential knee pain and injuries and help improve lunging performance.

1. Introduction

Knee joint is one of the most injured sites among badminton players (Jérgensen & Winge, 1987; Shariff, George, & Ramlan, 2009; Yung, Chan, Wong, Cheuk, & Fong, 2007), with patellar tendinopathy and patellofemoral pain rate up to 42.7%. Athletes with knee pain showed conservative and compensatory movements, which would lead to reduced performance and other potential injury risks (Huang, Lee, Lin, Tsai, & Liao, 2014; Lin, Hua, Huang, Lee, & Liao, 2015).

The high incidence of overuse chronic injuries was reported in the knee (Jérgensen & Winge, 1987), which may result from repetitive lunge loading accumulations. However, few comprehensive information about the knee joint motions (kinematics), moments (torques), contact forces and tissue stress during right-forward, right-backward, left-backward and left-forward lunges was revealed. The computational modelling technique, such as musculoskeletal (Delp et al., 2007) and finite element (Besier, Gold, Beaupré, & Delp, 2005) simulation, was widely applied in the clinical studies in recent year.

This project was aimed to reveal the knee joint kinematics and kinetics and investigate the contact force and cartilage von Mises stress via subject-specific musculoskeletal modelling analysis and finite element simulation based on the medical images.

2. Methods

This project involved two main sections, including **1**) lab-based lunges experiments, and **2**) subject-specific and knee finite element model construction based on medical images (CT/MRI).

2.1 Equipment

1) Lab-based experiments: An in-lab simulated badminton court was setup following our previously published protocol (Mei, Gu, Fu, & Fernandez, 2017), which is similar with other recent in-lab studies (Kuntze, Mansfield, & Sellers, 2010; W. K. Lam, Ding, & Qu, 2017). An eight-camera VICON motion capture system (Vicon Metrics Ltd., Oxford, United Kingdom), synchronized with an in-ground AMTI 3D force plate (AMTI, Watertown, MA, United States) and 16-channel wireless DELSYS Trigno surface EMG system (Delsys, Boston, MA, United States), were taken for the lunges experimental data collection.

The marker set used in this project was recently published in one of our studies (Mei, Gu, Xiang, Baker, & Fernandez, 2019), which has been validated previously (Hamner & Delp, 2013; Rajagopal et al., 2016). The capturing rate for marker trajectory from Vicon, ground reaction force from AMTI and muscle activity from Delsys were set at 200Hz, 1000Hz and 1000Hz, respectively.

2) Medical imaging collection: Athletes recruited for this project participated the session of knee joint CT scanning via a Optima CT540 (GE Medical Systems, Milwaukee, WI) and MRI scanning using a 3.0T SIGNA scanner (GE Medical Systems, Milwaukee, WI) in the local hospital. Medical images were used to segment the geometries of bone, cartilage and soft tissues using Mimics 21.0 (Materialise NV, Leuven, Belgium), then exported as 3D 'STL' geometry files (**Figure 1**).

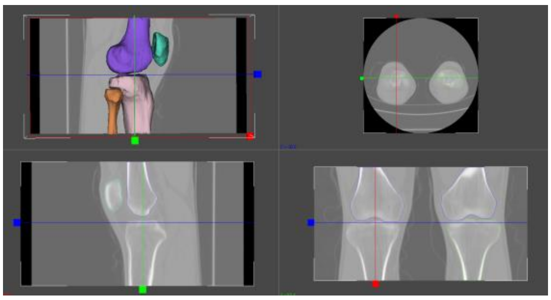

Figure 1 Segmentation of knee joint from CT images using Mimics

3) Subject-specific modelling and Finite element simulation: Subject-specific musculoskeletal model was adjusted and revised based on the geometry features, followed by the data post-procession performed in the OpenSIM 3.3 following the established workflow (*Scale - Inverse Kinematics - Inverse Dynamics - Static Optimization - Joint Reaction* analysis) (Delp et al., 2007).

The 3D 'STL' geometry of knee joint (femur, patellar, tibia, fibula, and cartilages etc.) was meshed in HyperMesh 2017 (Altair Hyper-Works, Troy, Michigan, USA) and exported as 'INP' files for Finite Element simulation in Abaqus CAE 2017 (SIMULA, Providence, Rhode Island, USA).

2.2 Participants

Twenty badminton athletes joint in this project, with 12 males (age: 20.5±3.1yrs, height: 176±4.9m, mass: 68.6±5.6kg) and 8 females (age: 19.3±4.1yrs, height: 165±3.8m, mass: 57.6±3.5kg). They are either (men's or women's) single or double players, with right hand and leg as dominant (aiming to control variables). All had no severe injuries (defined as terminating training or competition for 3 weeks) (van Mechelen, Hlobil, & Kemper, 1992) in the past six months prior to the test.

2.3 Procedures

All the experiments were conducted in a lab-simulated badminton court, facilitated with VICON motion capture, AMTI ground reaction force and wireless DELSYS surface EMG system. As per the lunging directions (right / left and forward / backward), the court and net was adjusted with the AMTI force plate as right leg lunge landing position. Different colours (**blue** for **Right-Forward**, **red** for **Right-Backward**, **black** for **Left-Backward**, and **yellow** for **Left-Forward**) were highlighted (**Figure 2**) so as to represent lunging directions (results section adopt the same approach to keep consistency).

Prior to the experiment, athletes were instructed to warm-up and get familiar with the lab environment and court setup. During the test, athletes initiated from the base position (left and right footprint) and performed the four lunges with required order. Four successful trials of each lunging direction were collected, which was defined as landing on the force plate with smooth and fast returning to the base position.

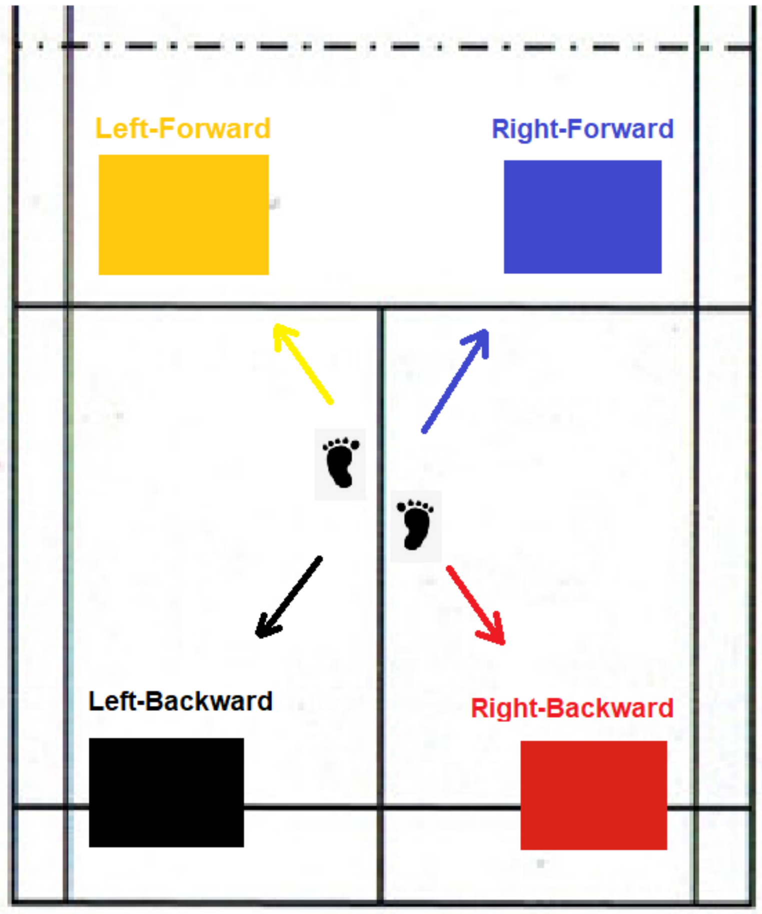

Figure 2 Illustration of lab-simulated badminton court for **Right-Forward**, **Right-Backward**, **Left-Backward** and **Left-Forward** lunges

2.4 Musculoskeletal modelling

During the lab test, one static trial was collected before lunging experimental data collection. The static marker positions were used to '***scale***' the model to subject-specific musculoskeletal models (**Figure 3**) as per the standard workflow (Delp et al., 2007), and the knee joint medial and lateral compartment were determined following previously established protocol (Lerner, Board, & Browning, 2016; Saxby et al., 2016). The '***Inverse kinematics***' (**IK**) algorithm minimized errors between virtual markers in the model and experimental marker trajectories to compute joint angles, '***Inverse Dynamics***' (**ID**) was performed to compute joints moment, '***Static Optimization***' (SO) was employed to compute muscle activation and forces. The estimated muscle activation was compared against measured surface EMG signals to validate the model. The contact forces to the knee (femoral-tibia and patellofemoral joints) in the anterior/posterior (**x**), superior/inferior (**y**), and medial/lateral (**z**) directions were computed using '***Joint Reaction***' (JR) analysis.

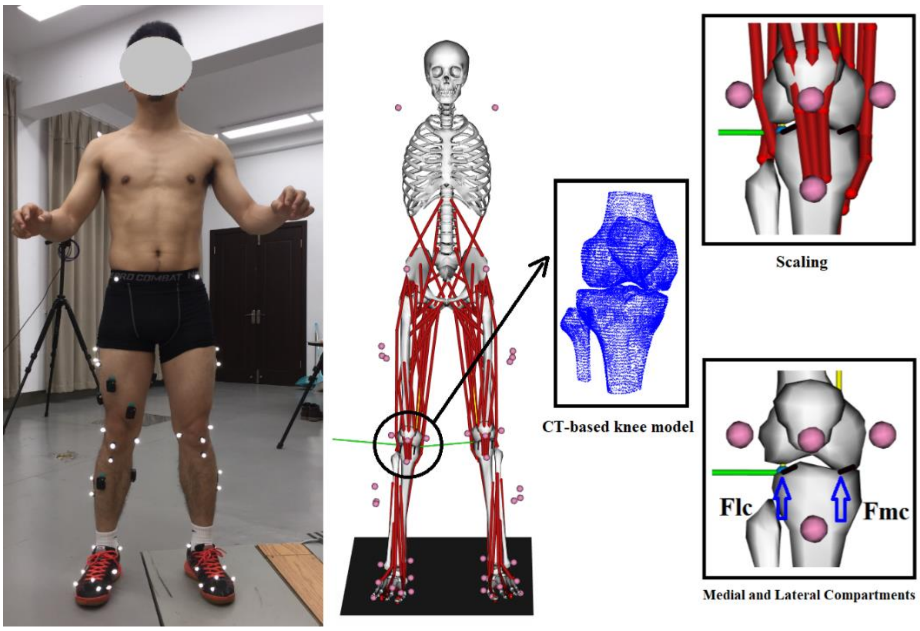

Figure 3 Framework of musculoskeletal modelling

2.5 Finite element modelling

The model of patellofemoral joint was constructed following a previous framework specifically designed for the in-vivo patellofemoral joint cartilage stress estimation (Besier et al., 2005). The model includes five parts, with femur, patellar and tibia bones, and femur and patellar cartilages (**Figure 4**). The bones were defined as rigid body, while materials properties of cartilages (femoral & patellar) were set as isotropic elastic with a Young's modulus of 6MPa and Poisson ratio of 0.47 (Besier et al., 2005). Quadriceps muscle forces estimated from static optimization were applied as pulling load applied to the patella as highlighted in the model (**Figure 4**).

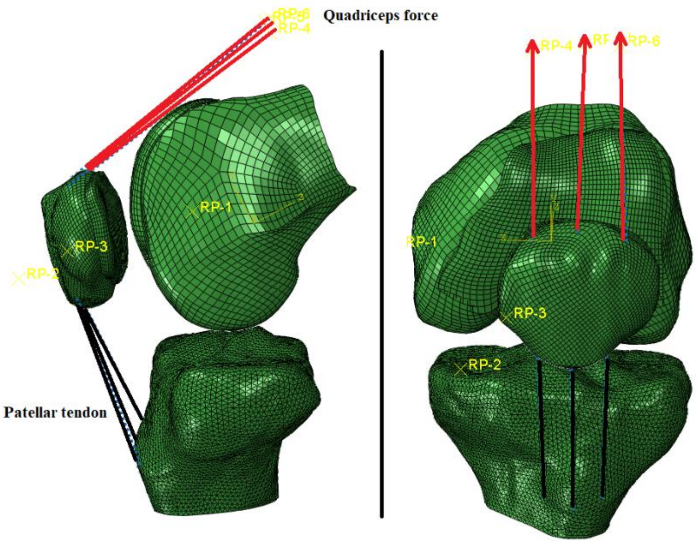

Figure 4 Construction of knee joint FE model in Abaqus

2.6 Statistical analysis

This project mainly focused on the stance of lunges from different directions. As the time varying characteristics of the knee joint angles, moments, and contact forces, the open source Statistical Parametric Mapping 1D package (SPM1D), which relies on

Random Vector Field theory to account for data variability, was utilized for the statistical analysis (Pataky, 2010). The significance level was set at $p < 0.05$.

3. Results

The stance was divided into braking phase and propulsion phase at the midpoint (50%) (Lam, Ding, et al., 2017) for analysis of knee angles, moments and contact forces. As the lunging steps landing with right foot on the force plate, a threshold of 20N in the vertical ground reaction force was set as to determine the foot landing and pushing-off (**Figure 5**).

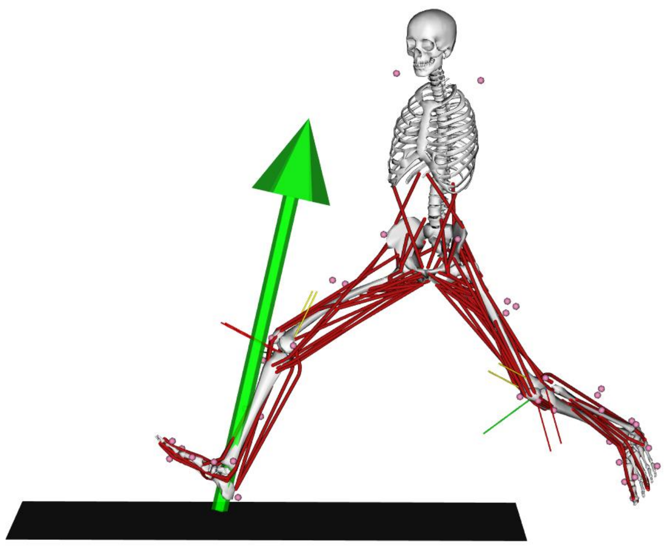

Figure 5 Illustration of lunging stance with ground reaction force (green arrow)

3.1 Knee kinematics (unit: degree)

As presented in the **Figure 6**, the knee joint exhibited no significance in the sagittal plane (flexion/extension), but significant higher abduction (-7.16±0.65°) and internal rotation (34.83±1.42°) were observed during push-off in **Left-Backward** lunge.

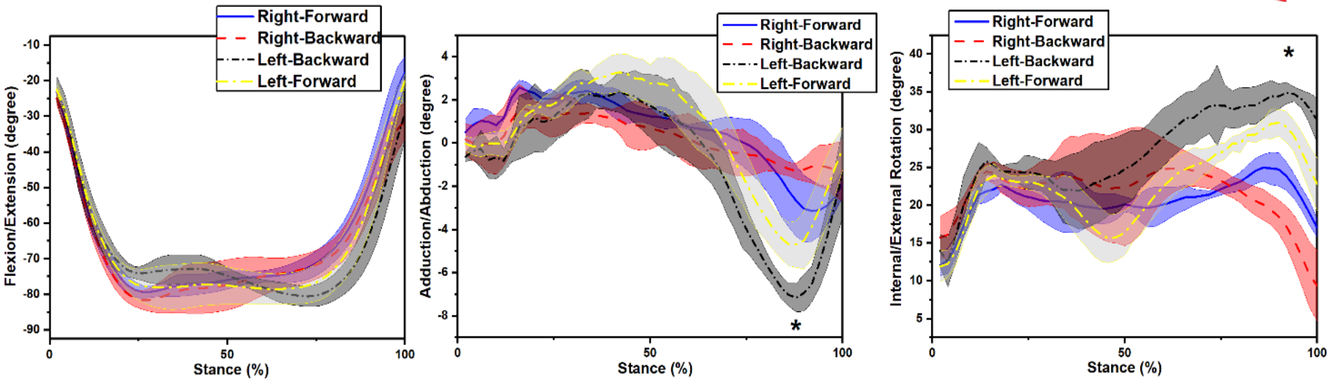

Figure 6 Knee joint angles (flexion as negative '-', abduction as negative '-' and internal rotation as positive '+') during stance

3.2 Knee kinetics (unit: Nm/kg)

Difference in the knee joint moment was found while landing. Significantly higher flexion moment was found while landing in **Right-Forward** (-2.62±2.27Nm/kg) lunge, however, higher extension moment was observed during **Left-Backward** (2.26±0.18Nm/kg) lunge in weight-acceptance phase. The **Right-Backward** (0.88±0.53Nm/kg) lunge showed higher adduction moment while landing.

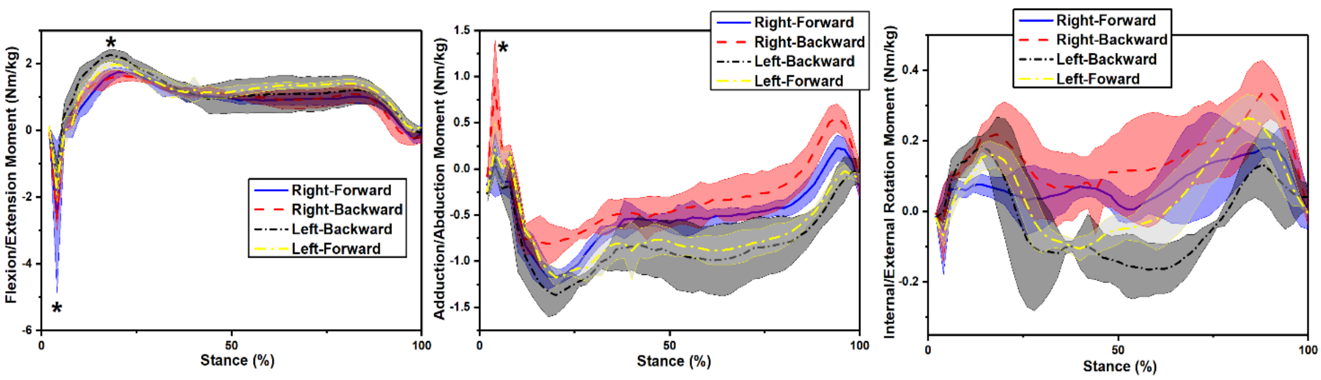

Figure 7 Knee joint moments (flexion as negative '-', abduction as negative '-' and internal rotation as positive '+') during stance

3.3 Knee contact forces (unit: BW)

As shown in the **Figure 8**, the total knee contact force (***a***) and contact forces to the medial and lateral compartments (***b***) were illustrated, and graphs below presented the total knee axial contact force (***c***), contact force in the medial compartment (***d***) and lateral compartment (***e***).

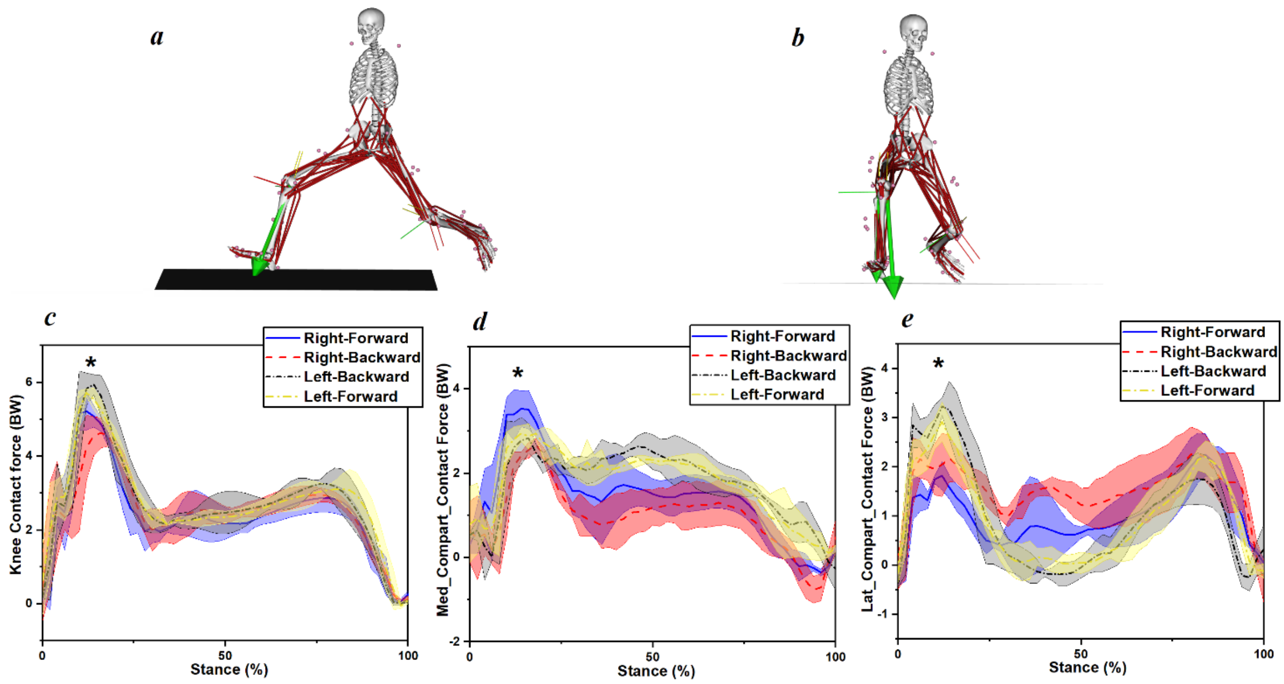

Figure 8 Total knee contact force (***c***) and contact forces to the medial (***d***) and lateral (***e***) compartments during lunging stance

Significantly ($p < 0.05$) larger in the total knee contact force in weight-acceptance phase during stance was found in the **Left-Backward** (5.94±0.28BW) and **Left-Forward** (5.72±0.12BW) directions. The greater contact force in the medial compartment was observed in weight-acceptance during stance was found in the **Right-Forward** (3.53±0.43BW) direction, while **Left-Backward** (3.23±0.18BW) and **Left-Forward** (2.91±0.4BW) lunges presented greater force in the lateral compartment during weight-acceptance.

3.4 Patellofemoral joint contact force (unit: BW) and cartilage Stress (unit: MPa)

The compressive patellofemoral joint contact force in the weight-acceptance phase during stance was presented in the **Figure 9**, with significantly higher force in the **Left-Backward** (3.23±0.18BW) and Left-Forward (2.91±0.4BW) directions.

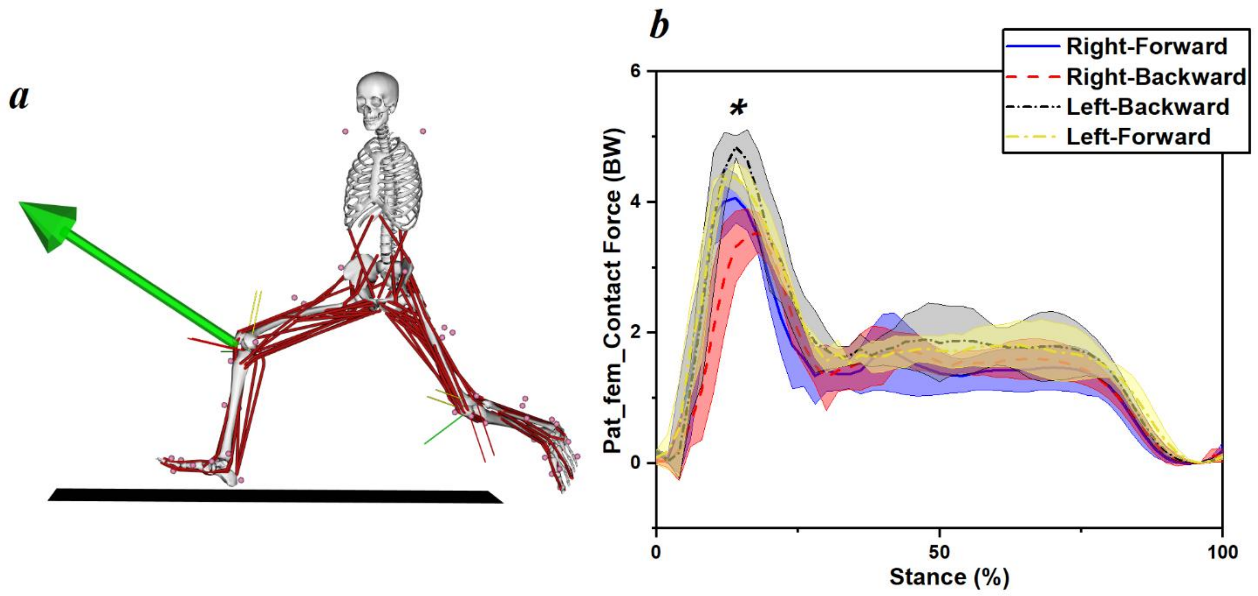

Figure 9 Illustration of patellofemoral joint contact force (***a***) and compressive contact force (BW) during lunging stance (***b***)

The quadriceps (vastus lateralis, vastus medialis, vastus intermedius and rectus femoris) muscle forces calculated from *Static Optimization* in musculoskeletal modelling were applied as the external load in the Finite Element simulation (see Figure 4). The muscle activations have been validated against the experimental surface EMG signals. The patellofemoral joint was simulated with knee in the ~70° position with maximal ground reaction force and muscle activation (forces), as in the **Figure 10**, the contact stress distributed on the patellar cartilage and femur cartilage were presented. The peak von Mises stress (MPa) were further manifested in the **Figure 11**, with peak patellar cartilage stress value of **6.73MPa**, **6.32MPa**, **7.57MPa**, and

7.25MPa, and peak femur cartilage stress value of **6.53MPa**, **6.29MPa**, **7.49MPa**, and **7.39MPa** during the **Right-Forward**, **Right-Backward**, **Left-Backward** and **Left-Forward** lunges.

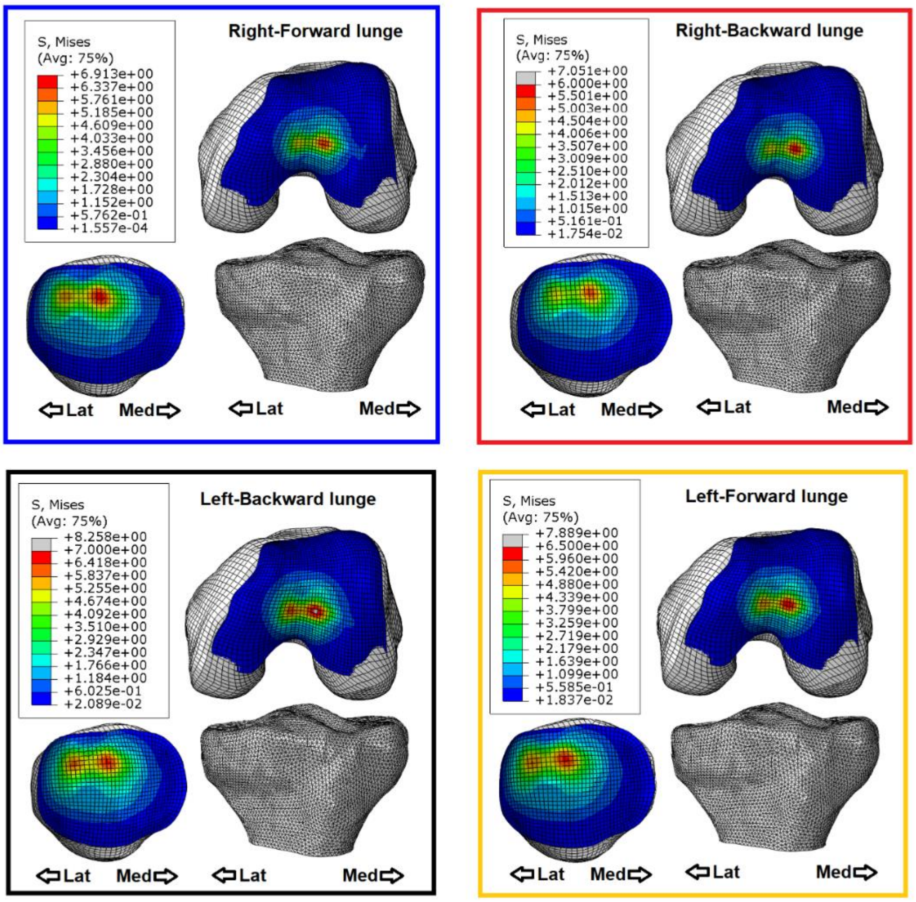

Figure 10 Stress (von Mises, MPa) distribution on the patellar and femur cartilages

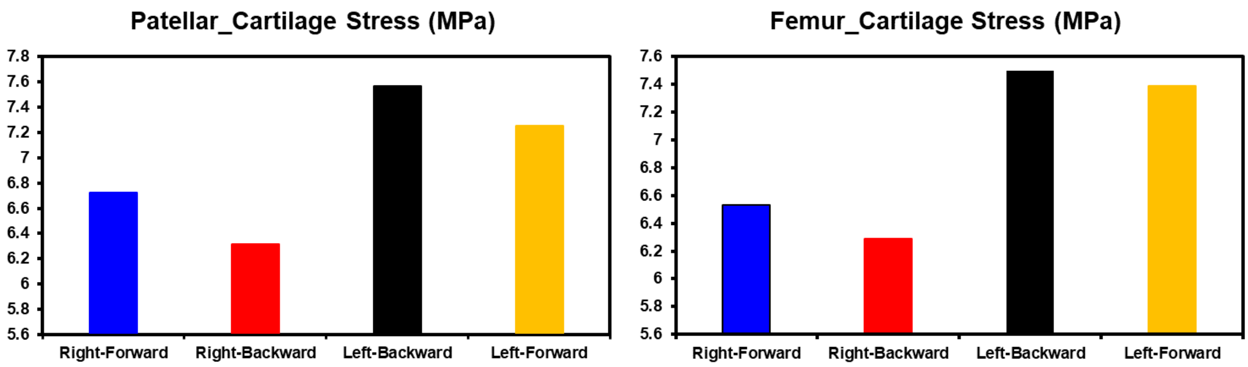

Figure 11 Peak von Mises Stress on patellar and femur cartilages during lunges

4. Discussion

This project investigated the knee joint kinematics, kinetics and contact forces during Right-Forward, Right-Backward, Left-Backward and Left-Forward lunges among Chinese athletes in the lab-simulated badminton court. Key findings indicated that the knee motions of the adduction/abduction and internal/external rotation were significantly different especially during the Left-Backward lunges. Greater knee flexion moment was found during Right-Forward lunges, following with larger extension moment in Left-Backward lunges during the weight-acceptance phase. The Right-Backward lunges presented greater adduction moment. The Left-Backward and Left-Forward lunges exhibited greater total knee contact force, while Right-Forward lunge had larger contact force in the medial compartment. Left-Backward and Left-Forward lunges showed larger contact force in the lateral compartment of knee joint, patellofemoral joint and patellar and femoral cartilages.

Before acknowledging findings from this project, one consideration should be noted that all the tests were performed in the lab-simulated court, which might be different from real-scenario training and competition. However, sufficient time for warm up and lab familiarization was permitted to minimize potential influence before experiment, which were consistent with recent studies (Huang et al., 2014; Kuntze et al., 2010; W. K. Lam, Ding, et al., 2017; Lin et al., 2015; Mei et al., 2017). To address this issue, a follow-up research about the on-court monitor of lower extremity loading via the IMU wearable sensor is initiated, and the research proposal will be submitted shortly for the BWF 2019-2020 Research Grant application.

To validate our results, the lunging stance time and approaching velocities were 0.78s and 1.88m/s, 0.86s and 1.98m/s, 0.69s and 2.25m/s, 0.73s and 2.1m/s for Right-Forward, Right-Backward, Left-Backward and Left-Forward, respectively. Together with the magnitude of measured ground reaction force, these results were compared against recent studies (Kuntze et al., 2010; Lam et al., 2018; Lam, Ding, et al., 2017; Lam, Ryue, et al., 2017).

As for the observed difference of the knee kinematics (abduction/adduction and internal/external rotation) in Left-Backward lunges during push-off phase, these may be attributed to the altered braking and pushing-off strategies while performing the backhand and backcourt lunges (as the body back facing the net). The backhand shuttle-returning from this position has been the most vulnerable and easily being stroke by opponent during competition. The shorter stance duration (0.69s) and fast approaching velocity (2.25m/s) are the additional evidence. A faster completion of Left-Backward lunge and returning to base position (preparing for next defensive shuttle-return) are also manifested by the greater knee extension moment, which was previously reported as a key factor for performance (Cronin, McNair, & Marshall, 2003).

Although no difference observed in flexion/extension angle during stance and abduction/adduction angle in weight-acceptance phase, the higher flexion moment in Right-Forward and adduction moment in Right-Backward deserved special attention, as the loadings are accumulating during familiar and comfortable movements as well (which tend to be ignored by athletes and coaching). Once the accumulative loads exceeding the tolerance threshold of motor system, the overuse injuries would occur either during training or competition. This lead to the necessity of monitoring the load accumulation dynamically and during real-scenario situations. Our follow-up research would mainly focus on the monitor of dynamic loads from lab towards in-court training and competition.

Knee pain is another issue commonly reported among badminton athletes. The observed in-court knee tape and support are additional evidence. Consistent with mentioned above, the total knee contact forces were found to be significantly higher during Left-Backward and Left-Forward lunges during weight-acceptance. Additional results presented in the Figure 8 explained that Right-Forward lunges mostly bear the medial compartment of knee joint while Left-Backward and Left-Forward lunges distributed most impact on the lateral compartment.

To explicitly reveal the contribution of quadriceps contribution on the knee loadings, the estimated average *vastus lateralis*, *vastus medialis*, *vastus intermedius* and *rectus femoris* forces (normalized to body weight) from the Static Optimization were 1.77BW, 0.96BW, 1.03BW and 1.1BW during Right-Forward, 1.47BW, 0.68BW, 0.88BW and 0.91BW during Right-Backward, 2.37BW, 1.14BW, 1.33BW and 1.25BW during Left-Backward, and 2.07BW, 0.98BW, 1.04BW and 1.18BW during Left-Forward. It could be found that the lateral regions of quadriceps contributed greatly during left side (backward and forward) lunges. While applying the external muscle force from mentioned above into the Finite Element simulation, consistent findings were observed in the patellofemoral joint compressive contact force and higher concentrated von Mises stress in the patellar and femoral cartilages. Knowledge of this part may provide implications that the four separate muscles in quadriceps should be trained and developed equally and simultaneously to prevent unequal loading distribution in cartilages and ligaments, or even patellar dislocation due to laxity of ligaments.

5. Conclusion

This project investigated the knee joint angles, moments, contact forces and cartilages stress during badminton lunges to the Right-Forward, Right-Backward, Left-Backward, and Left-Forward directions in Chinese athletes. Key findings were found in the Left-Backward and Left-Forward lunges with higher knee contact force and cartilage stress loading, which may link to knee pain. Additionally, the larger flexion and adduction moments in the Right-Forward and Right-Backward should also be noted as potential factors contributing to overuse injury risks. Quadriceps muscle force contributions were revealed that could assist the training program for developing these muscles, so as to prevent potential knee pain and injuries and help improve lunging performance.

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