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Short communication

Biomechanical modeling of deep squatting: Effects of the interface contact between posterior thigh and shank

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ABSTRACT

Epidemiological studies indicate that occupational activities that require extended deep knee flexion or kneeling are associated with a higher prevalence of knee osteoarthritis. In many sport activities, such as a catcher in a baseball or a softball game, athletes have to make repetitive deep squatting motions, which have been associated with the development of osteochondritis dissecans. Excessive deep knee flexion postures may cause excessive loading in the knee joint. In deep knee flexion postures, the posterior aspect of the shank will contact the posterior thigh, resulting in a compressive force within the soft tissues. The current study was aimed at analyzing the effects of the posterior thigh/shank contact on the joint loading during deep knee flexion in a natural knee. An existing, whole body model with detailed anatomical components of the knee (AnyBody) has been adopted and modified for this study. The effects of the posterior thigh/shank contact were evaluated by comparing the results of the inverse dynamic analysis for two scenarios: with and without the posterior thigh/shank contact force. Our results showed that, in a deep squatting posture (knee flexion 120+ degrees), the posterior thigh/shank contact helps reduce the patellofemoral (PF) and tibiofemoral (TF) normal contact forces by 42% and 57%, respectively.

1. Introduction

Some occupational activities in mining, construction, and manufacturing require workers to maintain kneeling or deep knee flexion postures for extended periods of time, which would potentially increase the risk of the development of knee osteoarthritis (OA) (Cooper et al., 1994; Bernard et al., 2010; Reid et al., 2010). In some sport activities, such as a catcher in a baseball or a softball game, athletes have to make repetitive deep squatting motions, which were associated with the development of osteochondritis dissecans (OCD) (McElroy et al., 2018; Accadbled et al., 2018). OCD may potentially progress to OA in later stage. Excessive deep knee flexion postures may cause excessive loading in the knee joint, leading to OCD or OA.

There are two types of experiments for quantifying knee joint loads: cadaver tests *in vitro* and human subject tests *in vivo*. Musculoskeletal models are currently the primary means for quantifying muscle and joint forces in the knee, either *in vivo* or *in vitro*. The knee joint loads obtained by different approaches differ substantially (Mason et al., 2008). Generally, the knee joint loads calculated by inverse dynamics in human subject studies are lower than those obtained in cadaver studies. For example, for deep squatting at a knee flexion angle of 110+ degrees, the patellofemoral (PF) contact forces calculated in human subject studies (Dahlkvist et al., 1982; Sharma et al., 2008; Reilly and Martens, 1972; Komistek et al., 2005) range from 2.7 to 5.2 times body weight (BW) whereas those obtained in cadaver studies (Singerman et al., 1994, 1999; Mason et al., 2008) range from 5.1 to 8.9 times BW.

In deep squatting, the posterior aspect of the shank will contact the posterior thigh, resulting in a compressive force within the soft tissues. Zelle et al. (2007) found that thigh-shank contact force for each leg reached 34 ± 9.7 % BW during squatting. Zelle et al. (2009) further analyzed the effects of the thigh-shank contact on knees that experienced a total knee arthroplasty surgery; they found that, at maximal flexion (155°), the thigh-shank contact helped reduce the knee joint contact force by approximately 40%. Zelle et al.'s (2009) model was static, considered only the tibiofemoral (TF) joint, and did not include muscles. The effects of the shank/thigh contact on the joint load during deep squatting for natural knee *in vivo* have not been quantified. The goal of the current study is to evaluate the effects of the interface contact between posterior thigh and shank on the joint loading during deep squatting using a biomechanical model.

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2. Method

The setup of the motion markers for the measurements of the whole body kinematics is similar to a previous study (Buczek et al., 2010). A 14-camera Vicon Nexus system (Oxford Metrics Ltd., Oxford, England) was used to capture the motion marker trajectories at 100 Hz. The data of the ground reaction forces were collected at 1200 Hz via two force plates (Model OR6-6-2000, Advanced Mechanical Technology Inc., Watertown, MA, USA). A healthy male subject (mass 70 kg, height 1.68 m) participated in the study by squatting five times at a self-selected pace. The test protocol was approved by the Institutional Review Board of the National Institute for Occupational Safety and Health.

The interface contact pressures between the posterior thigh and shank were measured using a pressure sensor film (Model 5101, TekScan, Boston, MA, USA) (Fig. 1a, Left). The pressure sensor film (112×112 mm) contained a 44×44 array of sensors and was calibrated by using the manufacturer recommended standardized setup and method. The contact force (F_n) was obtained by the mathematical integration of contact pressure over the contact surface: $F_n(t) = \sum_{i=1}^{44}\sum_{j=1}^{44} p(t, x_i, y_j)\Delta x \Delta y$ (Fig. 1a), with t and $p(t,x,y)$ being the time and pressure, respectively; $x_i = i\Delta x, y_j = j\Delta y$, and $\Delta x = \Delta y = 2.5$ mm, $i, j = 1, 2, \ldots 44$. The time-dependent center of the pressure $(x_c(t), y_c(t))$ was calculated by: $x_c(t) = (1/F_n)\sum_{i=1}^{44}\sum_{j=1}^{44} p(t, x_i, y_j)x_i\Delta x\Delta y$ and $y_c(t) = (1/F_n)\sum_{i=1}^{44}\sum_{j=1}^{44} p(t, x_i, y_j)y_j\Delta x\Delta y$.

An existing, whole body model with detailed anatomical components of the knee (AnyBody v6.0, Repository 2.0) has been adopted. The existing AnyBody model was modified via a uniform scaling method (Winter, 2005) based on the subject's body mass and height to make the model "subject-specific". The effects of the mass and mass inertial properties of the whole body segments (lower/upper extremity, trunk, neck, and head) were included in the inverse dynamic modeling. The knee model includes bony segments of the tibia, femur, and patella (Klein Horsman et al., 2007). The motions of the TF and PF joints are represented by 11-degree-of-freedom (DOF), in which the TF joint has six DOF and the PF joint has five DOF due to the restriction of the rigid patellar ligament. The model includes a total of 159 muscles in the lower extremity. Each of the quadriceps includes four muscles: rectus femoris, vastus lateralis, vastus intermedius, and vastus medialis, which contain 2, 8, 6, and 10 musculotendon units, respectively, – a total of 26 musculotendon units.

The major modification of the existing model to fit the scenario for deep squatting is the implementation of the contact force between the posterior surface of the shank and thigh (Fig. 1b). The distributed contact pressure in the posterior thigh/shank contact interface was represented by using an equivalent contact force (F), which was treated as an external force applied on the thigh and shank in the inverse dynamic analysis. The location of the contact force was also determined experimentally. Assuming that the total contact force (F) is decomposed into a normal (F_n) and a shear component (F_f), the direction of F is determined by a parameter – contact force ratio, $\mu = F_f/F_n$. Mechanically, the contact forces applied on the posterior thigh and on the shank sides are a pair of action and reaction forces; they should cancel each other to maintain a mechanical equilibrium (Dooley et al., 2019). The normal contact force, F_n, was measured in the experiments, whereas the shear force, F_f, was obtained by a try-and-fit method in the numerical simulations. The parameter μ was adjusted such that the contact force applied on the posterior thigh is aligned to that applied on the shank.

The recruitment of the muscle forces was determined by using an inverse dynamic method combined with an optimization algorithm in AnyBody (Rasmussen et al., 2001), in which the maximal normalized muscle force (i.e., the muscle force divided by the physiologic cross-section area) is minimized. The effects of the posterior thigh/shank contact were evaluated by running the inverse dynamic simulations two times: once including the posterior thigh/shank contact force (F) and once without the posterior thigh/shank contact force ($F = 0$). The model inputs were the kinematics of the whole body and the magnitude and center of the thigh/shank interface contact forces. The forces in each of the muscles across the knee joint, the constraint forces in the TF and PF joints, and the ground reaction forces were calculated. The comparison of the predicted ground reaction forces to those measured using the force plates in the experiments served as a model validation.

3. Results

At the maximal knee flexion posture, the vectors of the forces acting on the thigh and shank are visualized and their orientations are adjusted by varying μ value (Fig. 1b). Once the forces acting on the thigh and shank are aligned, $\mu = \mu_0$ is determined. In the current tests, we have $\mu = \mu_0 = 0.62$.

The subject completed a squatting movement in approximately 12 s; the knee flexion angle changes from 0 to 120 degrees (Fig. 2a), corresponding to the standing and deep squatting posture, respectively. When the posterior thigh contacted the posterior shank, the contact force suddenly increased and reached a peak value of approximately 300 N (Fig. 2b). The duration of posterior thigh-shank contact lasted about three seconds in the tests.

The vertical normalized ground reaction force measured in the tests, which was the sum of the forces at both feet, was compared with the model predictions that include or ignore the effects of the posterior thigh/shank contact (Fig. 2c). At the start of the test, the subject was in a static upright standing posture and the normalized ground reaction force was 1.0 BW. During the up-down squatting tasks, the normalized ground reaction force fluctuated in a range of approximately 4% around that for the static standing of 1.0 BW. The predicted ground reaction force without including the effects of the posterior thigh/shank contact is closer to the experimental data than that including the effects of the posterior thigh/shank contact.

The posterior thigh/shank contact starts at a knee flexion of around 90 degrees and the normal thigh/shank contact force reached its peak value of approximately 300 N when knee flexion reached its maximum of around 120 degrees (Fig. 3a). The contact area at the peak contact force was approximately 84 cm^2.

The calculated quadriceps forces and PF contact forces in the superior/inferior (F_{si}), anterior/posterior (F_{ap}), and lateral/medial (F_{lm}) direction are shown in Fig. 3b, c, e, and g, respectively. The maximal PF contact force was observed in the anterior/posterior direction (F_{ap} in Fig. 3e), and it is in the normal contact direction between the patella and femoral segments. The predicted normalized TF contact forces in the anterior/posterior (F_{ap}), superior/inferior (F_{si}), and lateral/medial (F_{lm}) direction are shown in Fig. 3d, f, and h, respectively. The maximal TF contact force was observed in the superior/inferior direction (F_{si} in Fig. 3f), and this force is in the normal contact direction. The difference between the model predictions that include or ignore the posterior thigh/shank contact increases with the knee flexion angle, which starts around 90 degrees of knee flexion. At the deepest squatting posture (knee flexion 120 degrees), the calculated quadriceps forces (Fig. 3f), and the PF and TF normal contact forces (Fig. 3e and f) including the posterior thigh/shank contact are approximately 60%, 58%, and 43%, respectively, of those that ignore the posterior thigh/shank contact.

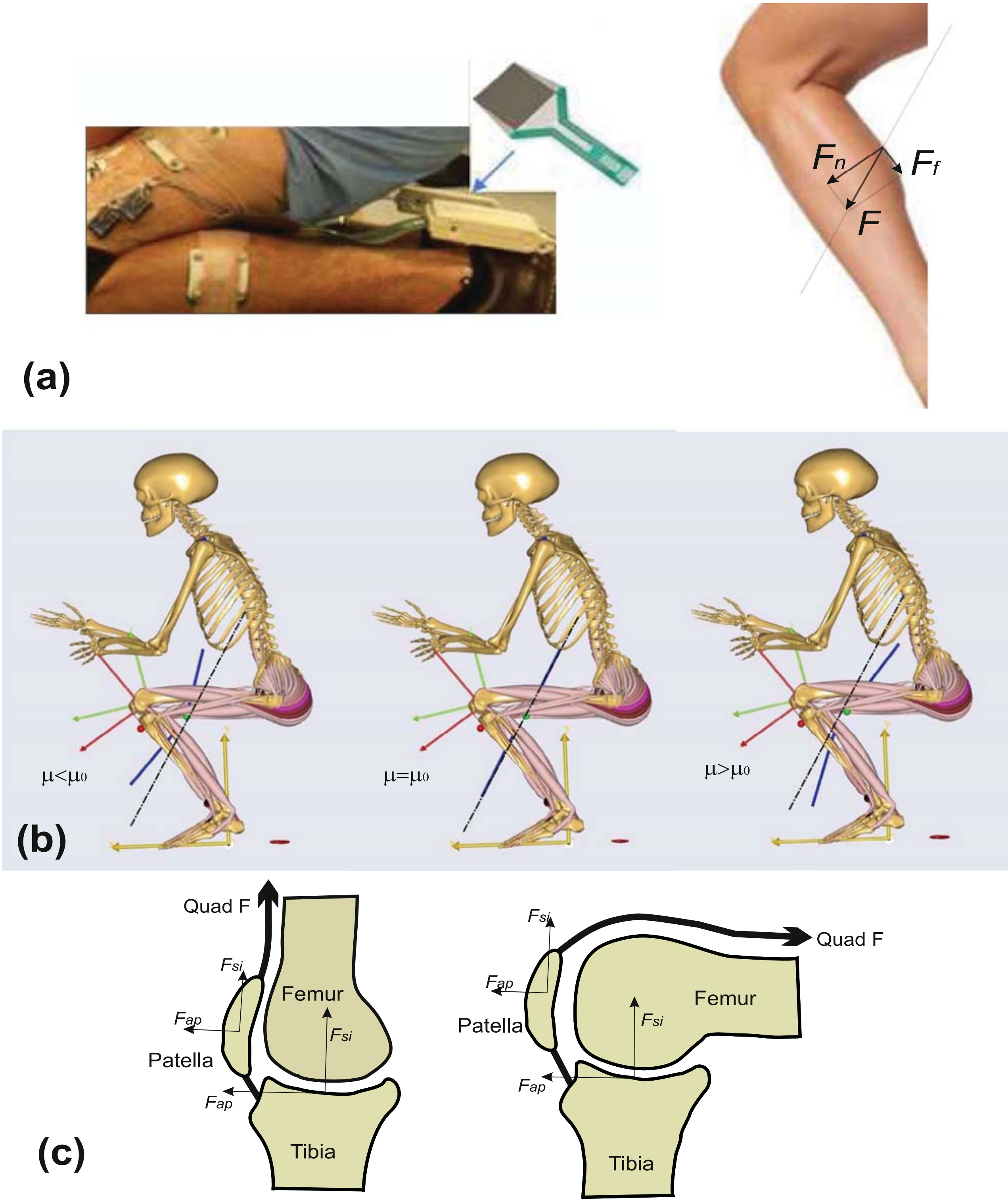

Fig. 1. Measurement of the posterior thigh/shank contact force and the biomechanical model. (a) Left: Measurement of the posterior thigh/shank contact force using a pressure sensor film (TekScan). Right: The posterior thigh/shank contact force (F) has a normal (F_n) and a shear (F_f) component. (b): Biomechanical model adopted from AnyBody (version 6.0) used in the study. The orientation of the contact force is adjusted until the force applied onto the posterior thigh is aligned with that applied on the shank (μ_0 = 0.62). (c): The definitions of the force directions in PF and TF joints. The joint forces are decomposed in superior/inferior (F_{si}), anterior/posterior (F_{ap}), and lateral/medial (F_{lm}) directions.

4. Discussion and conclusion

Our results (Fig. 3) show that the knee joint loading increases with increasing knee flexion, reaches its peak around 90–100 degrees flexion, and then decreases with further increases in the knee flexion due to the effects of the thigh-shank contact. Our results indicate that the knee contact forces are elevated when flexing around 90–100 degrees, increasing the risk of OA. In some

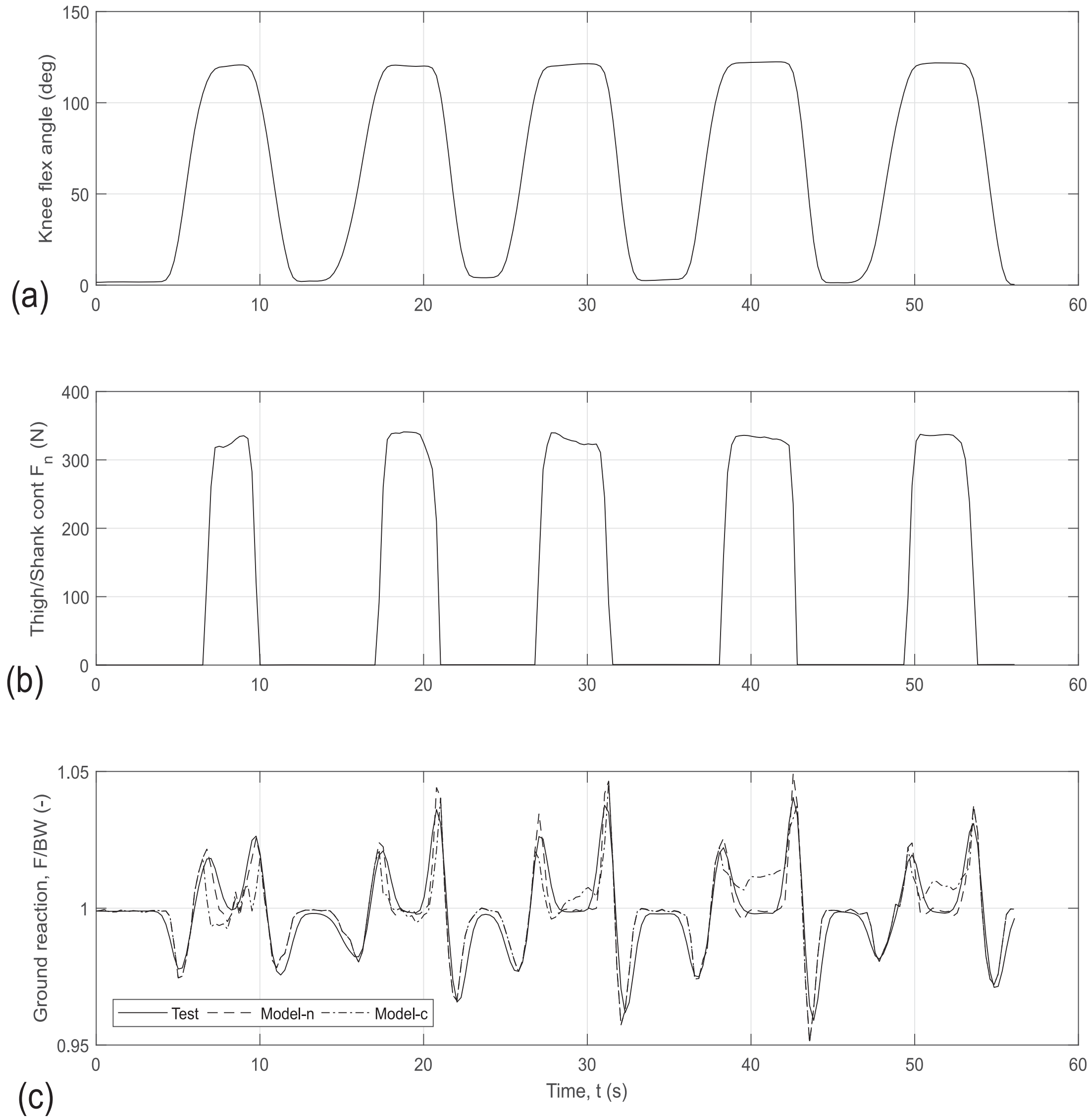

Fig. 2. Experimental measurements and comparison of the simulated ground reaction forces with experiments. (a): Knee flexion as a function of time. (b): The normal posterior thigh/shank contact force as a function of time. (c): Comparison of the time histories of the ground reaction force measured in the experiments ("Test", solid lines) with those calculated in the simulations that include ("Model-c", dash-dotted lines) and ignore ("Model-n", dashed lines) the effects of posterior thigh/shank contact.

occupational activities and sports, the knee joint would be maintained around this "unfavorable" flexion range for extended time; this would potentially increase the risk to develop knee OA.

The PF contact force without considering the posterior thigh/shank contact effects reached about 3.80 times BW at a deep squatting posture (knee flexion 120 degrees, F_{ap} in Fig. 3e). Our model prediction of the PF contact force is consistent with five previous relevant studies (Dahlkvist et al., 1982; Sharma et al., 2008; Reilly and Martens, 1972; Komistek et al., 2005), which are in a range from 2.7 to 6.7 (average 4.37) times BW.

The measured peak thigh/shank contact force at each leg was approximately 43% BW in the current study, compared to 34 ± 9.7 % BW reported in a previous study (Zelle et al., 2007). The difference in the thigh/shank contact force measures by the two studies is in a reasonable range, considering subjects' difference in anthropometry and muscular strength. In the current study, the thigh/shank contact was found to reduce the TF contact force by 57%, compared to 40% reported by Zelle et al. (2009). The difference between the two studies in the predicted effects of the thigh/shank contact on the joint loading is expected, because of the big differences between the two models. Compared to an earlier study (Zelle et al., 2009), the current simulations were obtained using a multi-body dynamic model that includes the whole body, muscles for the lower extremity, and more anatomical details of the knee joint. In addition, the current model includes the shear force component in the thigh/shank contact, whereas it was ignored in the previous study (Zelle et al., 2009).

Our model has been validated indirectly with the experimental observations in two aspects. First, at a static upright standing posture (i.e., knee flexion 0 degree), the model prediction on one-leg TF contact force (F_{si} in Fig. 3f) showed about half BW, which is physiologically reasonable. Secondly, the predicted time histories of the ground reaction forces agree reasonably well with the experimental measurements. The ground reaction force fluctuation during the squatting task is due to the mass inertial effects of the whole body segments, as well as the muscular forces that are needed to maintain the dynamic balance. The differences between the measurements and model predictions that include the effects of the posterior thigh/shank contact are likely caused by the misalignment of the contact force pair in the thigh/shank interface, resulting

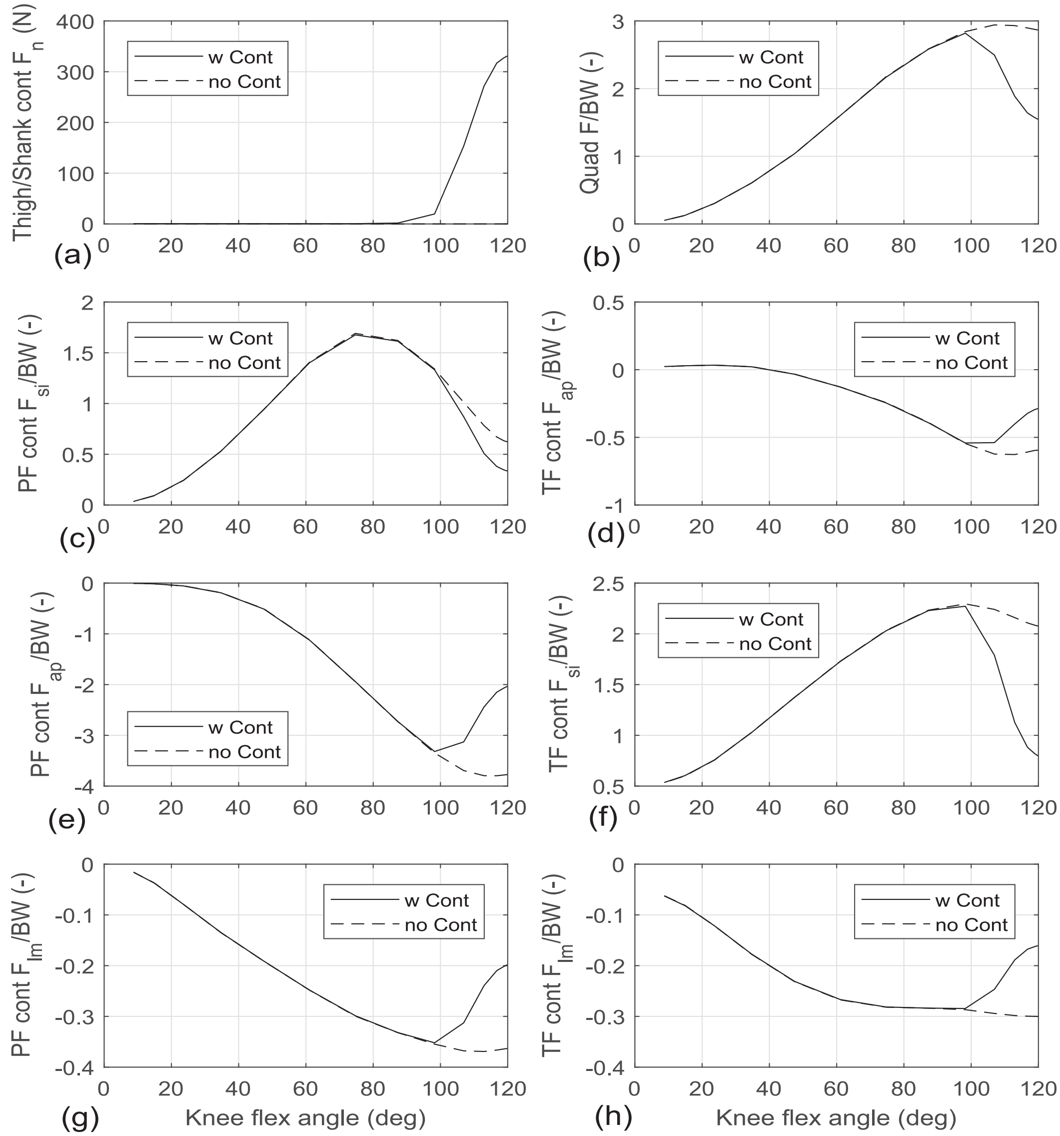

Fig. 3. Simulated effects of the posterior thigh/shank contact on the joint contact forces. (a): Measured posterior thigh/shank contact force as a function of knee flexion. (b): The calculated quadriceps force as a function of knee flexion. (c), (e), (g): The calculated PF contact force as a function of knee flexion in the superior/inferior (±) (F_{si}), anterior/posterior (±) (F_{ap}), and lateral/medial (±) (F_{lm}) direction, respectively. (d), (f), (h): The calculated TF contact force as a function of knee flexion in the anterior/posterior (±) (F_{ap}), superior/inferior (±) (F_{si}), and lateral/medial (±) (F_{lm}) direction, respectively. In plots (b-h), the solid lines ("w Cont") are the results that include the effects of the posterior thigh/shank contact whereas the dashed lines ("no Cont") are the results that ignore the effects of the posterior thigh/shank contact. All calculated forces have been normalized to the body weight (BW). The joint forces are defined in coordinate systems as shown in Fig. 1c. The curves represent the average of the values obtained from five squatting cycles.

in residual imbalance forces. The maximal difference between the predicted and measured ground reaction force is approximately 1% BW, indicating the model predictions are reasonable.

In summary, in a deep knee flexion posture, the posterior thigh and shank will contact each other, producing compressive force within the soft tissues around the joint, thereby affecting the joint loading. We analyzed the effects of the posterior thigh/shank contact on the joint loading during squatting. Our results showed that, in a deep squatting posture (knee flexion 120+ degrees), the posterior thigh/shank contact helps reduce the PF and TF normal contact forces by 42% and 57%, respectively. The current study indicated that the PF and TF contact forces reached their maximums around 100 degrees of knee flexion and that thigh/shank contact helped reduce the PF and TF contact force with further knee flexion. The model prediction supports the epidemiological studies that occupational activities that require extended crouching or squatting are associated with higher prevalence of knee OA.

Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention of the USA. Mention of brand name does not constitute product endorsement.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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