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Knee Joint Loading in Healthy Adults During Functional Exercises: Implications for Rehabilitation Guidelines

SUPPLEMENTAL VIDEO ONLINE

Primary goals for physical therapy after knee injury and surgery include return to full range of motion, full weight bearing, recovery of neuromuscular control, restoration of muscle strength, and ultimately the return to the preoperative activity level and function.[23,24] A gradual progression of joint loading is a key element of rehabilitation; therefore, the use of appropriate exercises to achieve the treatment goals while not overloading the injured joint is a difficult decision-making process for clinicians.

STUDY DESIGN: Controlled laboratory study.

BACKGROUND: The inclusion of specific exercises in rehabilitation after knee injury is currently expert based, as a thorough description of the knee contact forces during different exercises is lacking.

OBJECTIVE: To quantify knee loading during frequently used activities such as squats, lunges, single-leg hops, walking stairs, standing up, and gait, and to grade knee joint loading during these activities.

METHODS: Three-dimensional motion-analysis data of 15 healthy adults were acquired during 9 standardized activities used in rehabilitation. Experimental motion data were processed using musculoskeletal modeling to calculate contact and shear forces on the different knee compartments (tibiofemoral and patellofemoral). Using repeated-measures analyses of variance, contact and shear forces were compared between compartments and exercises, whereas muscle and average maximum femoral forces were compared only between exercises.

RESULTS: With the exception of squats, all therapeutic exercises imposed higher forces to the tibiofemoral joint compared to gait. Likewise, patellofemoral forces were greater during all exercises when compared to gait. Greater compartmental contact forces were accompanied by greater compartmental shear forces. Furthermore, force distribution over the medial and lateral compartments varied between exercises. With increased knee flexion, more force was imposed on the posterior portion of the condyles.

CONCLUSION: These results suggest that with careful selection of exercises, forces on an injured zone of the joint can be reduced, as the force distribution differs strongly between exercises. Based on the results, a graded exercise program for progressive knee joint loading during rehabilitation can be conceptualized. *J Orthop Sports Phys Ther 2018;48(3):162-173. Epub 6 Jan 2018. doi:10.2519/jospt.2018.7459*

KEY WORDS: *cartilage pressure, contact forces, knee, motion analysis, osteochondral injuries*

The selection and timing of specific rehabilitation exercises are currently more expert based than evidence based.[17,23,45] An example of this is the selection of weight-bearing versus non–weight-bearing exercises. Weight-bearing exercises are believed to induce compressive forces on the knee joint, which increase joint stability and decrease ligament strain.[34,43] In contrast, non–weight-bearing exercises are believed to reduce joint proprioception and synergistic muscle activation, consequently exposing the knee to increased shear forces.[1,6,18,21,36,43] However, to date, the magnitude of knee joint loading during rehabilitation exercises is not well documented.[28,37] Current rehabilitation protocols following cartilage repair surgery aim to account for the graft maturation by gradually incorporating exercises based on perceived joint load and to minimize shear stimuli that have been related to catabolic pathways in the cartilage tissue and undermine cartilage homeostasis.[17,23] Likewise, in the early stages of rehabilitation following anterior cruciate ligament injury and reconstruction surgery, rehabilitation protocols aim to avoid excessive ligament strain.[47,49] However, analysis of loading in terms of contact force (CF) magnitude and location during individual exercises is currently missing.[17]

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Strengthening thigh musculature is essential for optimal rehabilitation outcome after knee injury.[4] However, after rehabilitation, strength deficits often persist and negatively affect self-reported function and return to sport.[15,19,31] Consequently, knee stability and the ability to adequately dampen the impact forces are diminished, increasing the long-term risk for knee osteoarthritis.[19] Inclusion of rehabilitation exercises that specifically promote quadriceps musculature is therefore required because, even following accelerated weight-bearing protocols, strength deficits persist.[14]

In vivo measurements of knee CFs during functional activities are available, but only in patients who have undergone total knee arthroplasty with an instrumented implant. In these individuals, CFs have been documented during specific activities of daily living such as gait, stair climbing, kneeling, and lunging.[10,22] Integrated motion capture in combination with musculoskeletal modeling allows one to estimate the muscle, ligament, and knee CFs during functional activities such as gait, and results show good agreement with data measured using instrumented implants.[42] Applying this methodology to other functional activities, and especially rehabilitation exercises, would enable clinicians to quantify compartmental forces and their shear components in the knee joint.

The present study aimed to evaluate (1) the magnitude of the CFs and shear forces in the medial and lateral tibiofemoral and patellofemoral compartments, (2) knee muscle forces (ie, knee flexors and extensors), and (3) forces in different zones (anterior, mid, and posterior) of the femoral condyles during 9 weight-bearing exercises in a cohort of healthy adults. A better understanding of the knee CFs during different exercises may allow physical therapists to design more staged rehabilitation programs designed to minimize CFs and their shear components to prevent cartilage and ligament injury, while maximizing muscle strengthening.[35]

METHODS

Data Collection

Fifteen healthy adults (8 male, 7 female; mean ± SD age, 31 ± 6 years; body mass index, 22.35 ± 1.54 kg/m²) with no history of lower-limb injury were included in the study. The University Hospital Leuven Ethics Committee approved all study procedures (s56093), and all participants provided informed written consent. After a calibration trial, participants performed 5 repetitions of the following exercises: gait at self-selected speed, ascending and descending a standard 4-step staircase at self-selected speed, standing up from a chair without using the arms, sitting down on a chair from full standing without using the arms, squatting to 90° of self-perceived knee flexion with the arms fixed at the waist, forward and sideward lunging with the arms in the scapular plane and step length standardized to 80% of leg length, and single-leg hop from upright standing with the arms fixed at the waist. A detailed description of exercises as well as animations are provided in the **APPENDIX** (available at www.jospt.org). Exercises were executed barefoot to avoid confounding effects of shoes. Three-dimensional marker trajectories were recorded using a 10-camera Vicon system (100 Hz; Oxford Metrics, Oxford, UK), along with ground reaction forces using 3 ground-embedded force plates (1000 Hz; Advanced Mechanical Technology, Inc, Watertown, MA). Markers were placed according to a full-body Plug-in Gait (Oxford Metrics) marker set, and augmented with 3-marker clusters on the upper and lower arms and legs and anatomical markers on the sacrum, medial femur epicondyles, and the medial malleoli, resulting in 65 markers.[8]

Musculoskeletal Modeling

Muscle force and knee CFs were calculated using a previously validated scaled knee model, containing 6 degrees of freedom (DoF) for the patellofemoral and tibiofemoral joints.[29] This customized knee model was implemented into a generic lower extremity model.[3] The model included 44 musculotendon actuators spanning the hip, knee, and ankle, and 14 bundles of nonlinear springs, representing the major knee ligaments and posterior capsule. Cartilage contact pressures were calculated using a nonlinear elastic foundation formulation based on the penetration depth between overlapping cartilage surface meshes.[41] Combined uniformly distributed thicknesses of 4 mm and 7 mm were assumed in the tibiofemoral and patellofemoral joints, respectively.[13,16,25] An elastic modulus of 10 MPa and a Poisson ratio of 0.45 were assumed for cartilage.[2,5,30] The lower extremity model was implemented in SIMM (Motion Analysis Corporation, Santa Rosa, CA), using the Dynamics Pipeline (Symbolic Dynamics, Inc, Mountain View, CA) and SD/Fast (PTC, Needham, MA) to generate the multibody equations of motion. This model was found to be accurate for estimating CFs measured using instrumented implants, with a root-mean-square error below 0.33 body weight.[42]

The generic model was scaled to each participant's anthropometry and mass. Subsequently, pelvic translations, pelvic rotations, hip angles, knee flexion angle, and ankle angles were calculated at each frame of the movement cycle using inverse kinematics that minimized the weighted sum of squared differences between experimental and model marker positions.[32] Next, muscle forces required to generate the measured accelerations in the primary DoF (hip flexion, hip adduction, hip rotation, knee flexion, and ankle flexion) were calculated using the concurrent optimization of muscle activations and kinematics algorithm, which simultaneously calculates secondary knee kinematics (11 DoF) while minimizing the weighted sum of squared muscle activations and contact energy.[41] This algorithm allows the kinematics in the secondary tibiofemoral and patellofemoral DoF to evolve as a function of muscle, ligament, and CFs.[29,41,44] The resultant CF was calculated based on the contact pressure

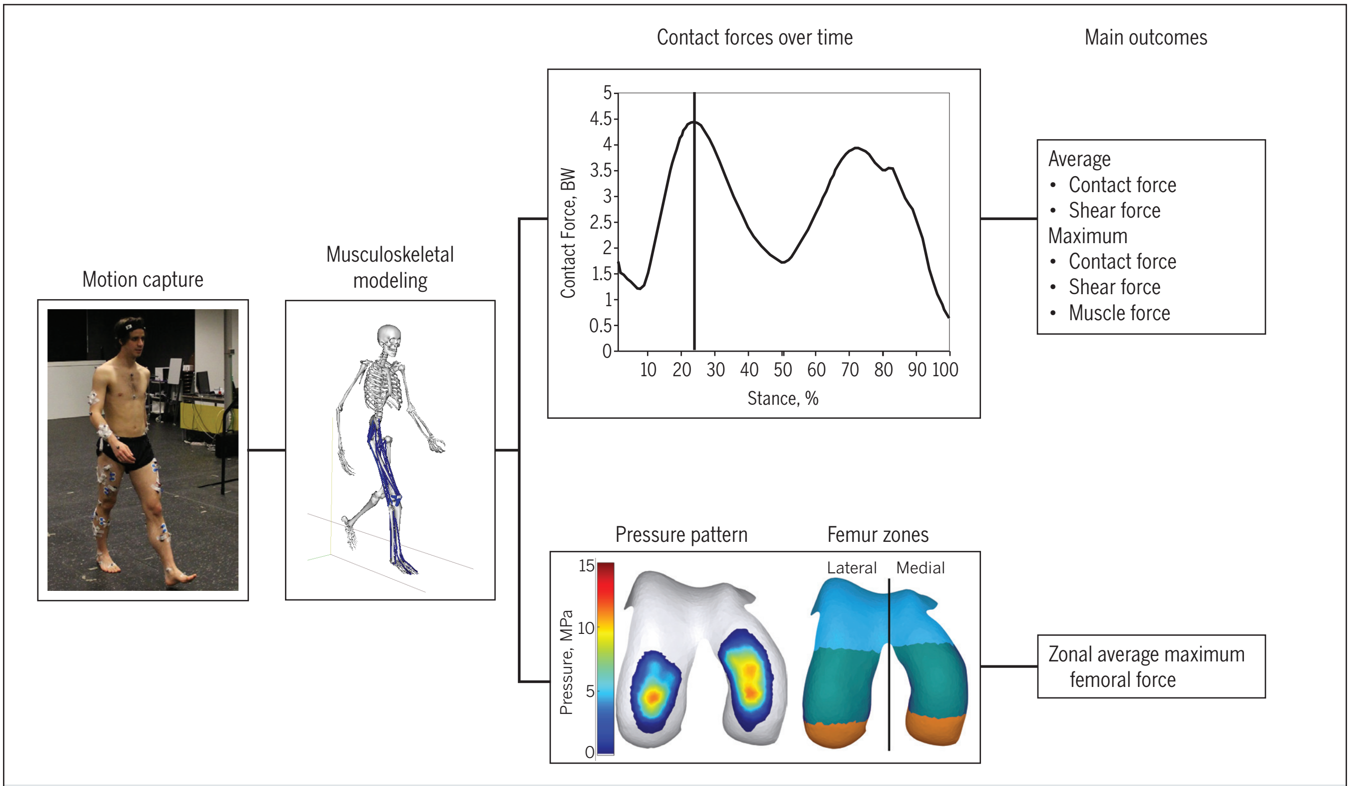

FIGURE 1. Data were collected and processed using musculoskeletal modeling to calculate cartilage loading. Contact forces were calculated, and the average and peak contact forces and shear forces were determined. The maximum contact pressure distribution was recalculated to the force distribution and was analyzed by determining the average maximum force in each zone. Abbreviation: BW, body weight.

and the contact area. The resultant CFs on the medial and lateral tibiofemoral compartments and patellofemoral joint were decomposed to estimate the net shear component. This calculation used the curvature information, based on the average mesh face normal of an area of 60 mm^2 around the application point of the CF, to define a local coordinate system used for the decomposition.

Data Analysis

For each exercise, the maximum and average magnitudes of the resultant CFs and shear forces of the total knee, as well as those for the medial and lateral tibiofemoral and patellofemoral compartments, were determined during the load-bearing phase. A detailed description of the analyzed phases, as well as the average trunk angles, is provided in the **APPENDIX**. The contact pressure distribution was recalculated to CF distribution, accounting for the area of individual mesh elements. Subsequently, the force distribution over the femur was analyzed by dividing the cartilage mesh in the anterior, mid, and posterior zones (**FIGURE 1**, **APPENDIX** Figure 1). For the tibiofemoral force, the maximum force on each element of the femoral condyle contacting the tibial surface during the exercise was determined and then averaged over the anterior, mid, and posterior zones of the medial and lateral condyles separately to obtain the average maximum tibiofemoral force in the respective zone.[38] For the patellofemoral force, the maximum force on each element of the femoral condyle contacting the patellar surface during the exercise was determined during the exercise and then averaged over the anterior, mid, and posterior zones of the femoral cartilage to obtain the average maximum patellofemoral force.[38] Likewise, the average maximum pressure for each zone was analyzed and reported in the **APPENDIX**. The maximum summed muscle force of the knee extensors (rectus femoris and vastus lateralis, vastus medialis, and vastus intermedius) and knee flexors (medial and lateral gastrocnemii, biceps femoris long head and short head, semimembranosus, and semitendinosus) throughout the load-bearing phase was determined. Data were averaged over 3 trials of each participant's right leg. To account for participant-specific mass, muscle forces, CFs, and shear forces were normalized to body weight.

Statistical Analysis

Maximum and average resultant CFs and shear forces on the medial and lateral tibiofemoral and patellofemoral compartments were compared between exercises and compartments using a 2-way repeated-measures analysis of variance (ANOVA). When a significant interaction effect was found, differences in CFs and shear forces were evaluated between compartments and exercises using dependent *t* tests. To evaluate between exercises, CFs and shear forces were compared to gait,

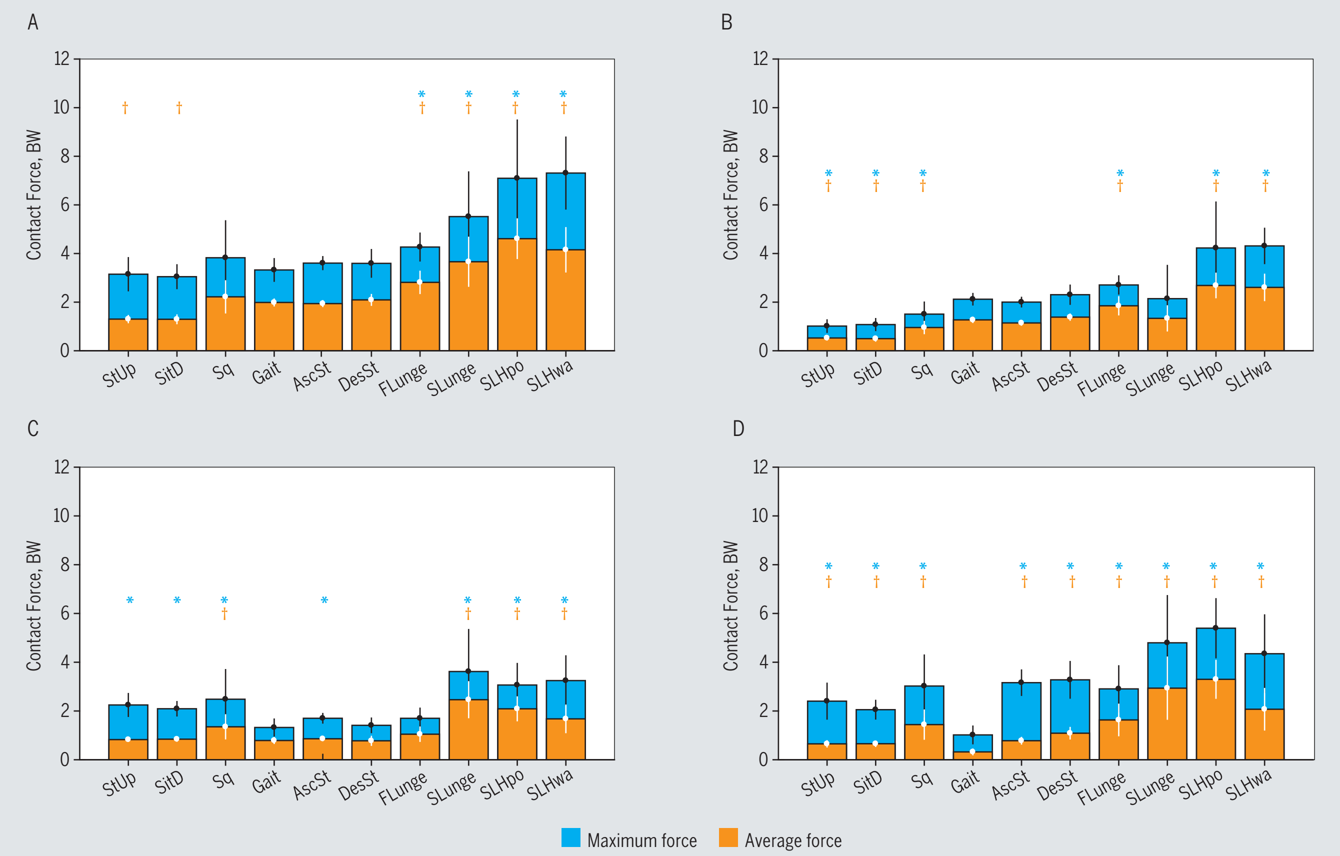

FIGURE 2. The magnitude of the maximum and average total tibiofemoral (A), medial tibiofemoral (B), lateral tibiofemoral (C), and patellofemoral (D) contact forces during the 9 exercises. Values are means and standard deviations. *Significant difference in maximum contact force. †Significant difference in average contact force compared to gait (Bonferroni-corrected $\alpha = .0056$). Abbreviations: AscSt, ascending stairs; BW, body weight; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

because gait was considered a milestone for progression toward more demanding exercises.[23,35] The average maximum tibiofemoral and patellofemoral force was compared between zones and exercises using 2-way repeated-measures ANOVAs. When a significant interaction effect was found, exercises were compared to gait for each zone using dependent *t* tests. A 1-way repeated-measures ANOVA compared total knee CFs and muscle forces between exercises, using dependent *t* tests to compare each exercise to gait when a significant effect for exercise was found. Significance level was set at .05, but Bonferroni corrected to compensate for the effect of multiple testing. All statistical tests were performed in SPSS (Version 24; IBM Corporation, Armonk, NY).

RESULTS

ANIMATIONS OF ALL EXERCISES, with the corresponding contact pressure patterns, are provided for a representative participant (**ONLINE VIDEO**, available at www.jospt.org).

Contact Forces

For total maximum and average tibiofemoral CFs, a significant main effect for exercise was observed ($P = .003$ and $P<.001$). For maximum and average compartmental CFs, a significant exercise-by-compartment interaction effect was observed ($P<.001$).

Post Hoc Comparison Between Exercises For the total tibiofemoral CF, maximum and average total tibiofemoral CFs were lowest during the sit-down task, with average total tibiofemoral CFs being significantly lower during sit-down and stand-up compared to gait. They were highest during the single-leg hop (push-off and weight acceptance). Both lunges (forward and sideward lunges) and the single-leg hop had higher maximum and average total tibiofemoral CFs than did gait (**FIGURE 2A**).

In the medial compartment, maximum and average CFs were lowest during stand-up and sit-down and similar to those during squat, but significantly lower than those during gait. They were highest during the single-leg hop and similar to those during the forward lunge, and significantly higher than those during gait (**FIGURE 2B**).

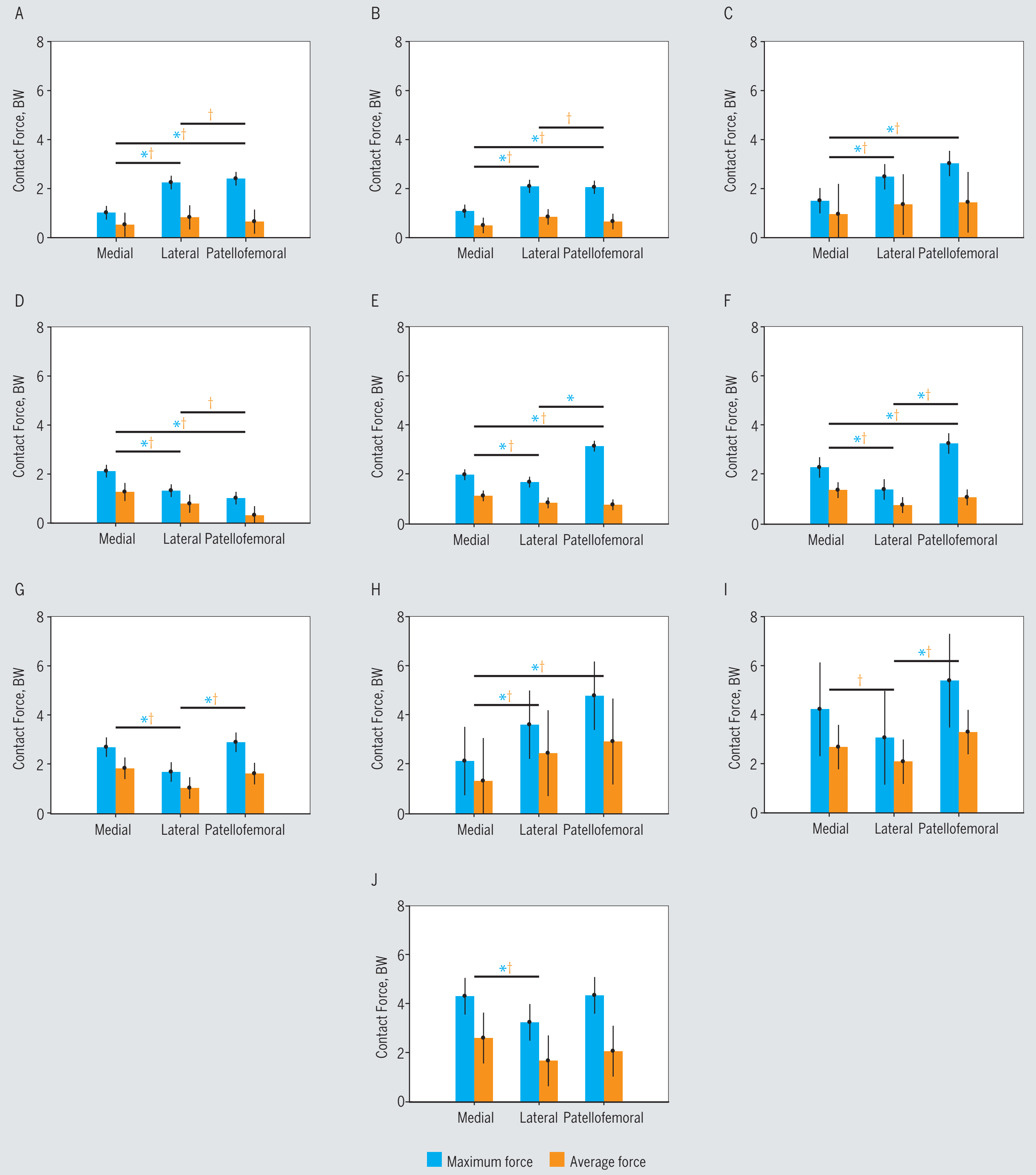

FIGURE 3. Distribution of the maximum and average contact forces over the different knee compartments. Values are means and standard deviations. *Significant difference between the maximum contact forces of 2 compartments. †Significant difference between the average contact forces of 2 compartments (Bonferroni-corrected α = .0125). (A) Stand-up, (B) sit-down, (C) squat, (D) gait, (E) stair ascent, (F) stair descent, (G) forward lunge, (H) sideward lunge, (I) single-leg hop push-off, (J) single-leg hop weight acceptance. Abbreviation: BW, body weight.

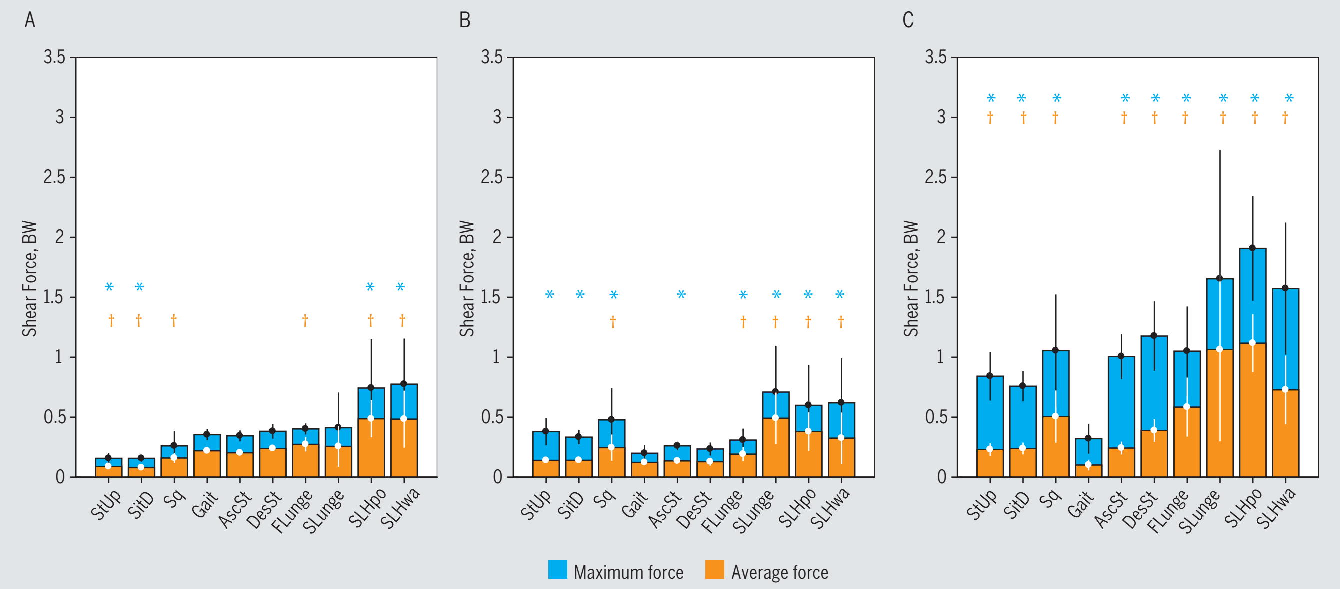

FIGURE 4. The magnitude of the maximum and average shear forces in the medial tibiofemoral compartment (A), lateral tibiofemoral compartment (B), and patellofemoral compartment (C) during the 9 exercises. Values are means and standard deviations. *Significant difference in maximum shear force compared to gait. †Significant difference in average shear force compared to gait (Bonferroni-corrected α = .0056). Abbreviations: AscSt, ascending stairs; BW, body weight; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

In the lateral compartment, maximum and average CFs were lowest during gait and stair descent, respectively, and highest during the sideward lunge. Compared to gait, maximum CF was significantly higher during stair ascent, sit-down, stand-up, squat, single-leg hop, and sideward lunge, whereas average CF was higher during the squat, single-leg hop, and sideward lunge (**FIGURE 2C**).

In the patellofemoral compartment, maximum and average CFs were lowest during gait and, when compared to all other exercises, significantly lower, with single-leg hop push-off having the highest maximum and average CFs (**FIGURE 2D**).

Post Hoc Comparison Between Compartments During gait, stair ascent and descent, forward lunge, and single-leg hop weight acceptance, maximum and average CFs were significantly higher on the medial than on the lateral condyle, whereas this was only confirmed for the average CF during single-leg hop push-off. Maximum and average CFs were significantly lower in the medial than in the lateral compartment during stand-up, sit-down, squat, and sideward lunge (**FIGURE 3**).

Shear Forces

For maximum and average shear forces, a significant exercise-by-compartment interaction effect was observed ($P<.001$).

Post Hoc Comparison Between Exercises In the medial compartment, maximum and average shear forces were lowest during stand-up and sit-down, respectively, and significantly lower than those during gait. They were highest during the single-leg hop and significantly higher than those during gait. Average shear force was significantly lower during squat and was significantly higher during forward lunge than during gait (**FIGURE 4A**). In the lateral compartment, maximum and average shear forces were lowest during gait and highest during the sideward lunge. Maximum and average shear forces were significantly higher during forward lunge, squat, single-leg hop, and sideward lunge than those during gait. Maximum force was significantly higher during stair ascent, sit-down, and stand-up than that during gait (**FIGURE 4B**).

In the patellofemoral compartment, maximum and average shear forces were lowest during gait and highest during single-leg hop push-off. All exercises, compared to gait, had significantly higher maximum and average patellofemoral shear forces (**FIGURE 4C**).

Post Hoc Comparison Between Compartments Maximum and average shear forces in the medial compartment were significantly higher than those in the lateral compartment during gait, stair ascent, stair descent, and forward lunge. During single-leg hop, shear forces were not significantly different between medial and lateral compartments. Maximum and average shear forces in the medial compartment were significantly lower than those in the lateral compartment during stand-up, sit-down, and squat, whereas during sideward lunge, only the average shear forces were significantly lower in the medial than those in the lateral compartment (**FIGURE 5**).

During gait, average shear forces were significantly lower in the patellofemoral compartment than those in the medial tibiofemoral compartment. Average and

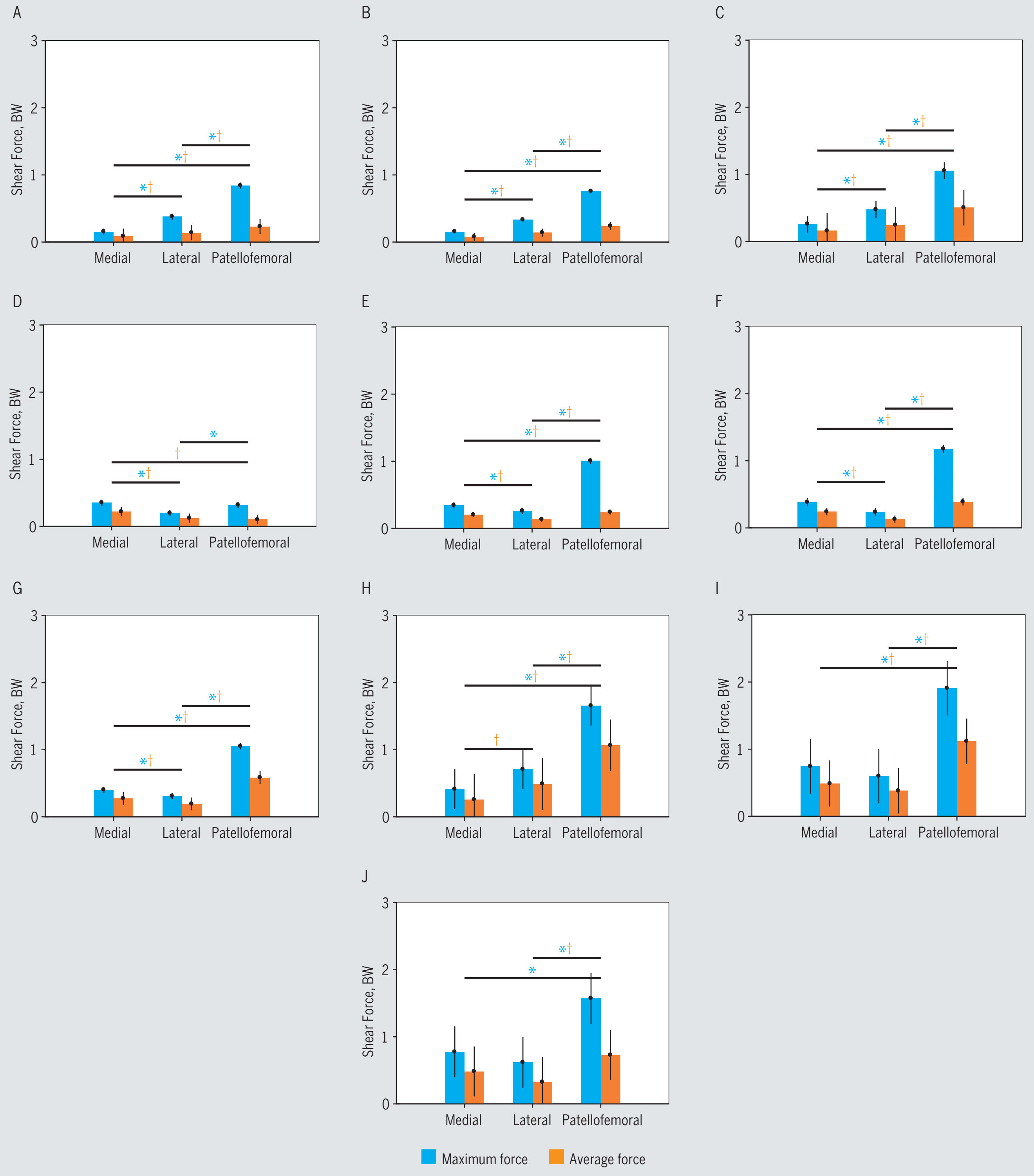

FIGURE 5. Distribution of the maximum and average shear forces over the different knee compartments. Values are means and standard deviations. *Significant difference between the maximum shear forces of 2 compartments. †Significant difference between the average shear forces of 2 compartments (Bonferroni-corrected $\alpha = .0125$). (A) Stand-up, (B) sit-down, (C) squat, (D) gait, (E) stair ascent, (F) stair descent, (G) forward lunge, (H) sideward lunge, (I) single-leg hop push-off, (J) single-leg hop weight acceptance. Abbreviation: BW, body weight.

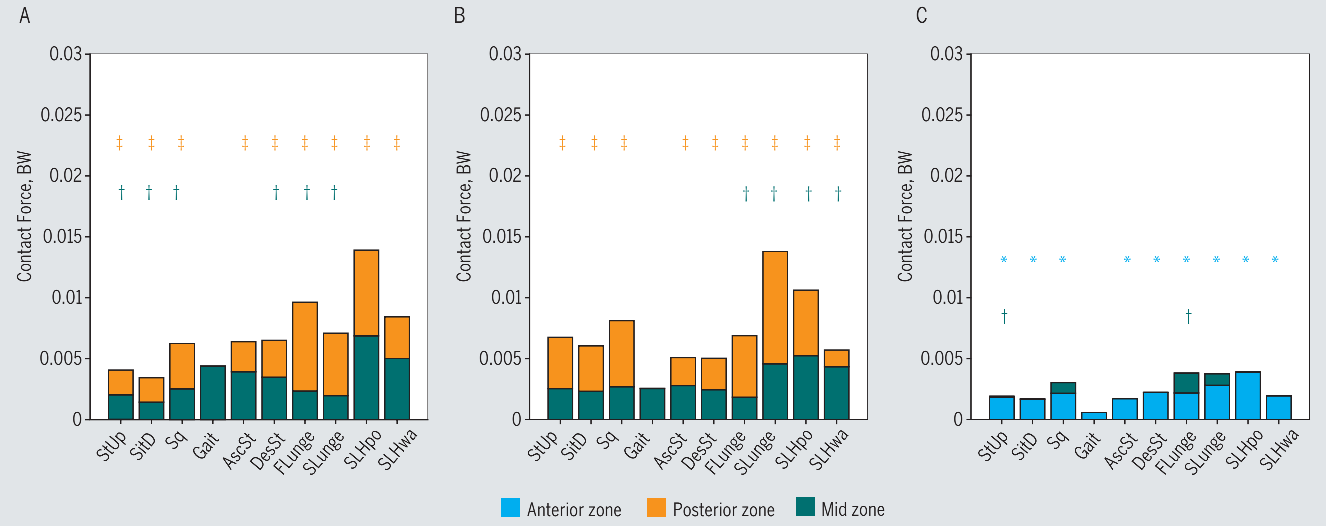

FIGURE 6. The average maximum tibiofemoral force on the anterior, mid, and posterior zones of the medial femoral condyle (A) and lateral femoral condyle (B). The average maximum patellofemoral force on the anterior, mid, and posterior zones of the femur (C). Values are means. *Significant difference in anterior zone pressure compared to gait. †Significant difference in mid zone pressure compared to gait. ‡Significant difference in posterior zone pressure compared to gait (Bonferroni-corrected α = .0056). Abbreviations: AscSt, ascending stairs; BW, body weight; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

maximum shear forces were significantly higher in the patellofemoral than those in the medial tibiofemoral compartment during stand-up, sit-down, squat, stair ascent and descent, lunges, and single-leg hop push-off, but this was only confirmed for the maximum shear force during single-leg hop weight acceptance. During all exercises, maximum patellofemoral shear forces were significantly higher than the shear forces in the lateral tibiofemoral compartment. Average patellofemoral shear forces were significantly higher than the shear forces in the lateral tibiofemoral compartment during all exercises, except during gait (**FIGURE 5**).

Average Maximum Tibiofemoral and Patellofemoral Forces in the Different Zones

A significant exercise-by-zone interaction was observed for average maximum tibiofemoral force on the medial and lateral condyles and for the average maximum patellofemoral force (all, $P<.001$).

Post Hoc Comparison Between Exercises The mid zones of the medial and lateral condyles experienced the lowest average maximum tibiofemoral force during sit-down and forward lunge, whereas this zone was most loaded during single-leg hop push-off. Compared to gait, the mid zone of the medial condyle presented significantly less average maximum tibiofemoral force during sit-down, stand-up, stair descent, sideward lunge, forward lunge, and squat. Compared to gait, the mid zone of the lateral condyle experienced significantly less average maximum tibiofemoral force during forward lunge and significantly higher average maximum tibiofemoral force during single-leg hop and sideward lunge (**FIGURES 6A** and **6B**). The posterior zones of the medial and lateral condyles experienced the lowest average maximum tibiofemoral force during gait, whereas they experienced the highest average maximum tibiofemoral force during forward and sideward lunges. All exercises imposed significantly more medial and lateral average maximum tibiofemoral force on the posterior zones than did gait (**FIGURES 6A** and **6B**).

The anterior zone of the femur experienced the lowest average maximum patellofemoral force during gait. Average maximum patellofemoral force was significantly higher during all exercises than during gait (**FIGURE 6C**). The mid zone experienced almost no average maximum patellofemoral force during gait, stair ascent and descent, and single-leg hop, whereas the highest average maximum patellofemoral force was experienced during forward lunge. Significantly higher average maximum patellofemoral force was imposed on the mid zone during stand-up and forward lunge than during gait (**FIGURE 6C**).

Muscle Forces

A significant main effect for exercise was observed for both flexor (P = .009) and extensor ($P<.001$) summed muscle forces.

Post Hoc Comparison Between Exercises Summed knee extensor muscle force was highest during single-leg hop push-off and lowest during gait. Summed knee flexor muscle force was highest during single-leg hop push-off, but lowest during sit-down. During all exercises, knee extensor muscle forces were significantly higher than those during gait, and knee flexor muscle force was significantly lower during sit-down, stand-up, and stair descent (**FIGURES 7A** and **7B**).

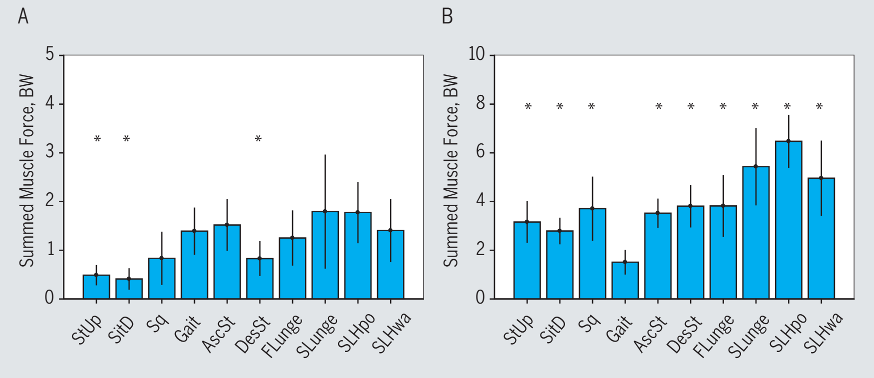

FIGURE 7. Summed muscle force of the knee flexors (A) and knee extensors (B) during each exercise. Values are means and standard deviations. *Significant difference between the muscle forces compared to gait (Bonferroni-corrected α = .0056). Abbreviations: AscSt, ascending stairs; BW, body weight; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

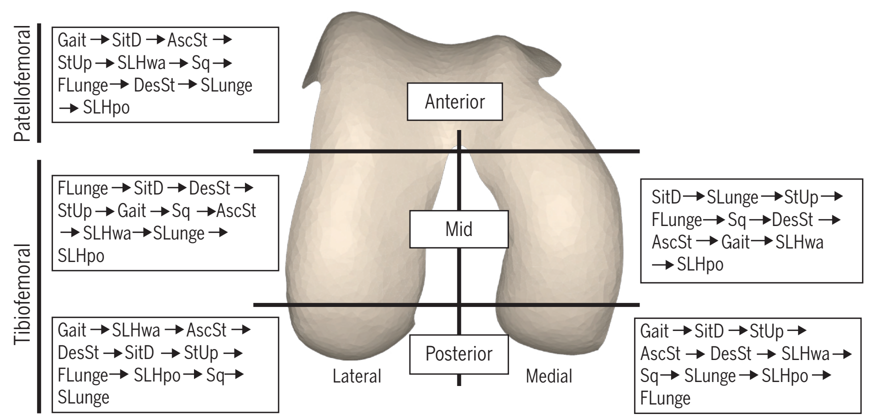

FIGURE 8. Graded exercise sequences, dependent on compartment involvement based on local loading (ie, average maximum zonal femoral force). Abbreviations: AscSt, ascending stairs; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

DISCUSSION

THIS STUDY EVALUATED KNEE contact and shear forces during 9 weight-bearing exercises. Most of the studied functional exercises are commonly used in lower-limb rehabilitation. Estimated loading on the tibiofemoral and patellofemoral joints can then be used to grade different exercises and provide insights for the staging of rehabilitation programs following knee injury or surgical intervention. During rehabilitation, the challenge is to protect the joint structures from excessive forces, while providing sufficient stimuli to regain muscle control and strength to restore normal function.

Tibiofemoral CFs were higher during all exercises compared to those during gait, except for those during sit-down, stand-up, stair ascent and descent, and squatting. Interestingly, although these exercises required greater knee flexion range of motion, the tibiofemoral CFs were equal to or lower than those during gait. Similar findings were previously observed using instrumented knee implants and can be explained by the bilateral nature of the tasks, distributing body weight over both lower extremities, and by the lack of foot-floor impact.[10,12,26] Consequently, these exercises can be used to train quadriceps muscle early in rehabilitation without exposing the tibiofemoral joint to high CFs. All exercises imposed higher patellofemoral CFs compared to gait, consistent with the deeper knee flexion angles and greater quadriceps involvement required from the exercises (**FIGURE 8**).[7,20,33]

A redistribution of CFs over the condyles was observed between exercises. During gait, similar to stair ascent and descent, forward lunge, and single-leg hop, the majority of the CFs pass through the medial condyle.[12,27,40] In contrast, the CFs were higher on the lateral than on the medial condyle during the stand-up, sit-down, squat, and sideward lunge exercises. These observations in a healthy cohort with uncorrected movement behavior suggest that differential loading of a specific compartment could be achieved by careful exercise selection. Specifically, forward lunges and walking stairs produced relatively lower forces in the lateral compartment, as did squat and sideward lunges in the medial compartment (**FIGURE 8**). Furthermore, during exercises with more knee flexion (eg, lunge and squat), the average maximum femoral force was more concentrated over the posterior zone of the condyles.[38] Similar findings were previously measured using fluoroscopy, showing more posteriorly located tibiofemoral contact points during deep knee flexion.[11,39,50]

As repaired (eg, cartilage) or reconstructed (eg, anterior cruciate ligament) structures are most vulnerable in the first months after surgical intervention, it is advisable to initially avoid excessive shear forces post surgery.[23,24,46,48] During all exercises, shear forces on the lateral condyle were significantly higher than those during gait, due to the increased CFs in the lateral compartment. Only forward lunge and single-leg hop presented increased shear forces in both the lateral and medial compartments, compared to gait. Therefore, inclusion of exercises characterized by high CFs and accompanying shear forces in both tibiofemoral compartments should be carefully timed in rehabilitation.

Restoration of muscle strength is one of the key elements for successful rehabilitation, requiring exercises that appropriately recruit the knee musculature.[4,23,24] All exercises resulted in significantly higher knee extensor force production, compared to gait, and consequently can be used to train the quadriceps muscles. Conversely, none of the exercises increased knee flexor muscle force production, indicating that other exercises need to be used to train the knee flexor musculature.

While these results provide important insights into knee loading during several exercises, they should be interpreted with respect to several limitations. First, healthy individuals were studied during unconstrained motion, in contrast to patients who may adapt movement patterns to avoid pain and therefore influence knee loading. Second, the elastic foundation model did not allow for the direct calculation of local shear forces. Instead, the components of the resultant force on each compartment were interpreted in relation to the cartilage curvature. Therefore, the effect of friction or tissue deformation is neglected, by which the magnitude of the shear forces may be underestimated. The presented approach assumes that geometry is the major contributor to shear, and therefore the relative comparison between exercises will not be affected. Third, neutral joint alignment was assumed for all participants. In patients with severe deformities or knee instability, this assumption may not be valid and could affect the force distribution over the medial and lateral condyles. Last, the model used in the current study comprises a generic knee model, with a uniformly distributed cartilage thickness. Therefore, the effect of physiologic variation in cartilage thickness on contact pressures and forces is not included in the current analysis. Despite these limitations, the estimated CFs were consistent with the previously reported CFs measured with instrumented implants,[10,11,22,26] with the higher CFs compared to other studies possibly explained by the inclusion of healthy young adults.[9,11,22]

The results of this study have the potential to contribute to biomechanically informed rehabilitation programs and can be used for conceptualizing an individualized rehabilitation program in which several factors, such as rehabilitation goal, injury location, surgical intervention, and tissue repair status, can be considered. A comprehensive overview of exercise progression based on the loading of different zones is proposed in **FIGURE 8**. All exercises can be used to train knee extensor musculature, as they resulted in higher knee extensor muscle force production compared to gait. To account jointly for the status of repair tissue and training the knee extensors, squat as well as stand-up and sit-down exercises can be introduced early in rehabilitation, as these result in CFs lower than during gait while providing an adequate training stimulus for the knee extensors. This is in contrast to the perception that squatting results in high knee loading and should only be introduced after full weight bearing has been allowed.[17,23] Furthermore, exercise selection may allow avoiding excessive loading of an injured or repaired osteochondral site. Indeed, forward lunges resulted in more medial loading compared to lateral loading, whereas the opposite was found during squat or sideward lunge. Likewise, in instances of lesions or repair surgery to the posterior section of the femoral condyles, the amount of knee flexion during lunges and squats should be restricted. Finally, with patellofemoral lesions or repair surgery, exercises should only gradually be introduced, as they all resulted in increased patellofemoral CFs and accompanying shear forces.

CONCLUSION

THIS STUDY ANALYZED CARTILAGE loading during functional activities and exercises and provides useful insight for the design of evidence-based rehabilitation programs. The results suggest that careful selection of functional exercises can be done to better control loading and shear forces at a knee-specific location or within a knee compartment. Consequently, inclusion of strengthening exercises can be progressed in a more evidence-based manner. ◉

KEY POINTS

FINDINGS: Relative loading of the lateral and medial tibiofemoral compartments varies based on the exercise performed. By diminishing compartmental loading, compartmental shear loading can be reduced.

IMPLICATIONS: These results can be used to conceptualize a graded rehabilitation program for progressive knee loading.

CAUTION: Only noninjured participants were included in the study, and patients may have different movement strategies due to pain, the injury, impairments, or joint alignment.

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APPENDIX

STUDIED EXERCISES

Five repetitions of the following exercises were measured. For each exercise, the load-bearing phase was analyzed.

- Gait: walking at self-selected speed across the motion lab (8 m). A trial was successful when each foot strike was on a separate force plate. Only the stance phase was analyzed, and was defined as the period during which the vertical component of the ground reaction force exceeded 20 N.
- Stair ascent: ascend a standard 4-step staircase (step height, 0.16 m; tread length, 0.31 m) at self-selected speed. Only the stance phase was analyzed, and was defined as the period during which the vertical component of the ground reaction force exceeded 20 N.
- Stair descent: descend a standard 4-step staircase (step height, 0.16 m; tread length, 0.31 m) at self-selected speed. Only the stance phase was analyzed, and was defined as the period during which the vertical component of the ground reaction force exceeded 20 N.
- Stand-up: rise from a chair, without using the arms, to full standing position. A backless and armless chair was used, and chair height was standardized to the height of the lateral femoral knee marker. Both feet and the chair were placed on a different force plate. Stand-up was analyzed from the instantaneous minimum in the vertical ground reaction force under the feet until the vertical ground reaction force started to fluctuate around body weight. Starting from the instant of maximum peak vertical ground reaction force above body weight, thereafter, the ground reaction force decreases below body weight until it again increases. The subsequent maximum was defined as the end of stand-up.
- Sit-down: sit on a chair from full standing, without using the arms. Sit-down was analyzed from the first 1.5% decrease in ground reaction force under the feet until the instantaneous minimum ground reaction force after maximum ground reaction force.
- Squat: squat down from upright standing to 90° of self-perceived knee flexion and rise. Participants started in upright standing, with arms fixed at the waist and both feet on a separate force plate. The squat was analyzed from the first 1.5% decrease in vertical ground reaction force until stabilizing in a zone around 1.5% of the ground reaction force.
- Forward lunge: from upright standing with arms in the scapular plane, step forward onto a separate force plate, lower the body until the trailing knee touches the ground, and return to starting position. Step length was standardized to 80% of the leg length. Forward lunge was analyzed when the stepping leg had contact with the force plate, determined as the period when the vertical ground reaction force exceeded 20 N.
- Sideward lunge: from upright standing with arms in the scapular plane, step sideward onto a separate force plate, lower the body until approximately 90° of knee flexion in the stepping leg, and return to starting position. Step length was standardized to 80% of the leg length. Sideward lunge was analyzed when the stepping leg had contact with the force plate, determined as the period when the vertical ground reaction force exceeded 20 N.
- Single-leg hop: perform a single-leg hop with the arms fixed at the waist. Single-leg hop was analyzed during 2 phases (ie, the push-off phase and weight-acceptance phase). Push-off ranged from the minimal vertical position of the sacrum marker to release of the force plate, determined as the vertical ground reaction force below 20 N. Weight acceptance ranged from ground contact (vertical ground reaction force exceeding 20 N) to the minimum vertical position of the sacrum marker.

TABLE

Average, Minimum, Maximum, and Range of Motion of the Trunk Angles During Each Exercise[*]

	Trunk Flexion[†]	Trunk Bending[‡]	Trunk Rotation[§]
Average			
StUp	–25.03 ± 11.3	–0.01 ± 0.5	0.45 ± 0.2
SitD	–25.03 ± 11.3	–0.01 ± 0.5	0.45 ± 0.2
Sq	–21.44 ± 9.2	0.18 ± 0.2	–0.05 ± 0.4
Gait	–10.23 ± 0.7	1.6 ± 3.3	1.35 ± 6.8
AscSt	–13.55 ± 1.0	–0.22 ± 6.2	0.29 ± 1.5
DesSt	–9.82 ± 1.5	0.21 ± 3.3	1.41 ± 1.7
FLunge	–11.54 ± 1.5	6.78 ± 2.3	2.83 ± 1.4
SLunge	–14.87 ± 2.9	–0.8 ± 1.5	2.53 ± 2.3
SLHpo	–21.98 ± 4.3	3.74 ± 8.2	4.27 ± 2.1
SLHwa	–17.43 ± 2.4	–0.04 ± 3.8	–0.65 ± 0.5
Minimum			
StUp	–41.11 ± 8.3	–2.03 ± 2.3	–1.37 ± 3.0
SitD	–41.11 ± 8.3	–2.03 ± 2.3	–1.37 ± 3.0
Sq	–35.29 ± 9.7	–1.83 ± 1.6	–2.8 ± 4.0
Gait	–12.49 ± 6.0	–6.34 ± 2.7	–9.53 ± 2.9

Table continues on A2.

APPENDIX

TABLE

Average, Minimum, Maximum, and Range of Motion of the Trunk Angles During Each Exercise* (continued)

	Trunk Flexion[†]	Trunk Bending[‡]	Trunk Rotation[§]
AscSt	–15.91 ± 6.2	–9.13 ± 2.9	–3.26 ± 3.3
DesSt	–12.51 ± 6.3	–5.67 ± 2.7	–3.26 ± 3.0
FLunge	–14.96 ± 5.9	–0.74 ± 2.4	–2.63 ± 7.7
SLunge	–19.5 ± 8.1	–5.95 ± 3.7	–3.15 ± 3.8
SLHpo	–28.25 ± 10.8	–11.83 ± 5.6	–3.3 ± 6.6
SLHwa	–20.94 ± 10.2	–6.3 ± 3.0	–3.53 ± 5.3
Maximum			
StUp	–7.71 ± 5.2	2.11 ± 2.5	2.36 ± 2.7
SitD	–7.71 ± 5.2	2.11 ± 2.5	2.36 ± 2.7
Sq	–6.07 ± 5.3	2.84 ± 3.7	3.53 ± 3.8
Gait	–8.32 ± 6.1	6.96 ± 2.2	10.04 ± 4.9
AscSt	–11.16 ± 6.3	8.63 ± 3.1	2.78 ± 2.3
DesSt	–6.42 ± 6.1	5.7 ± 2.2	4.56 ± 2.3
FLunge	–6.03 ± 4.8	10.02 ± 4.5	5.22 ± 7.8
SLunge	–7.39 ± 5.5	3.29 ± 7.0	7.07 ± 4.4
SLHpo	–13.47 ± 5.8	12.77 ± 7.0	10.02 ± 6.8
SLHwa	–13.18 ± 7.4	4.8 ± 5.2	1.97 ± 7.7
Range of motion			
StUp	33.4 ± 6.3	4.14 ± 2.2	3.73 ± 1.2
SitD	33.4 ± 6.3	4.14 ± 2.2	3.73 ± 1.2
Sq	29.22 ± 8.8	4.67 ± 2.8	6.33 ± 3.1
Gait	4.17 ± 1.5	13.29 ± 1.8	19.56 ± 5.4
AscSt	4.75 ± 1.3	17.76 ± 4.6	6.05 ± 2.2
DesSt	6.09 ± 1.7	11.37 ± 3.3	7.82 ± 3.0
FLunge	8.94 ± 3.0	10.75 ± 4.4	7.84 ± 3.4
SLunge	12.12 ± 5.0	9.25 ± 5.4	10.22 ± 4.2
SLHpo	14.78 ± 8.7	24.61 ± 9.1	13.32 ± 6.3
SLHwa	7.76 ± 5.8	11.1 ± 4.2	5.49 ± 4.9

Abbreviations: AscSt, ascending stairs; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.

**Values are mean ± SD degrees.*

[†] *Negative values indicate flexion and positive values indicate extension.*

[‡] *Negative values indicate contralateral bending and positive values indicate ipsilateral bending.*

[§] *Negative values indicate ipsilateral rotation and positive values indicate contralateral rotation.*

APPENDIX

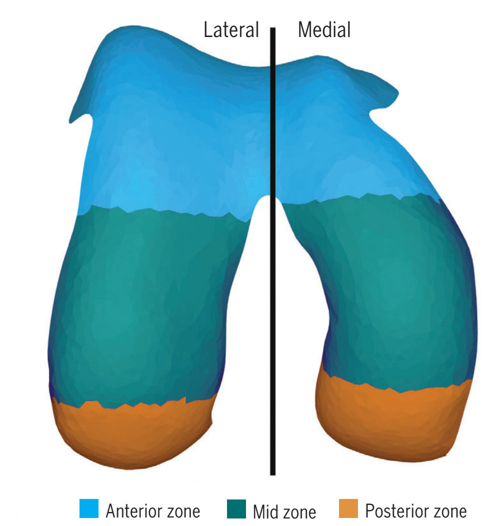

FIGURE 1. Division of the femoral cartilage in 3 zones, based on the method proposed by Peterfy et al.[38] The anterior zone was defined as the zone before the anterior end of the intercondylar notch. The mid zone was defined as the area between the anterior end of the intercondylar notch and 60% of the distance to the most posterior end of the femoral condyle. The posterior zone was defined as the area behind the line at 60% of the distance to the most posterior end of the condyle. For the analysis of patellofemoral contact pressure, the zones of the medial and lateral condyles were combined.

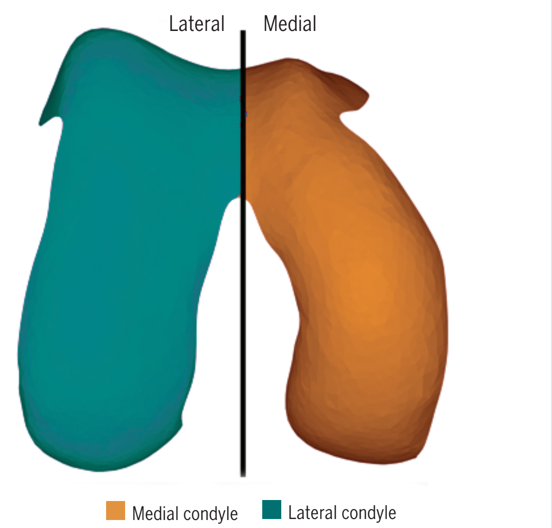

FIGURE 2. Division of the femoral cartilage into a medial and a lateral compartment.

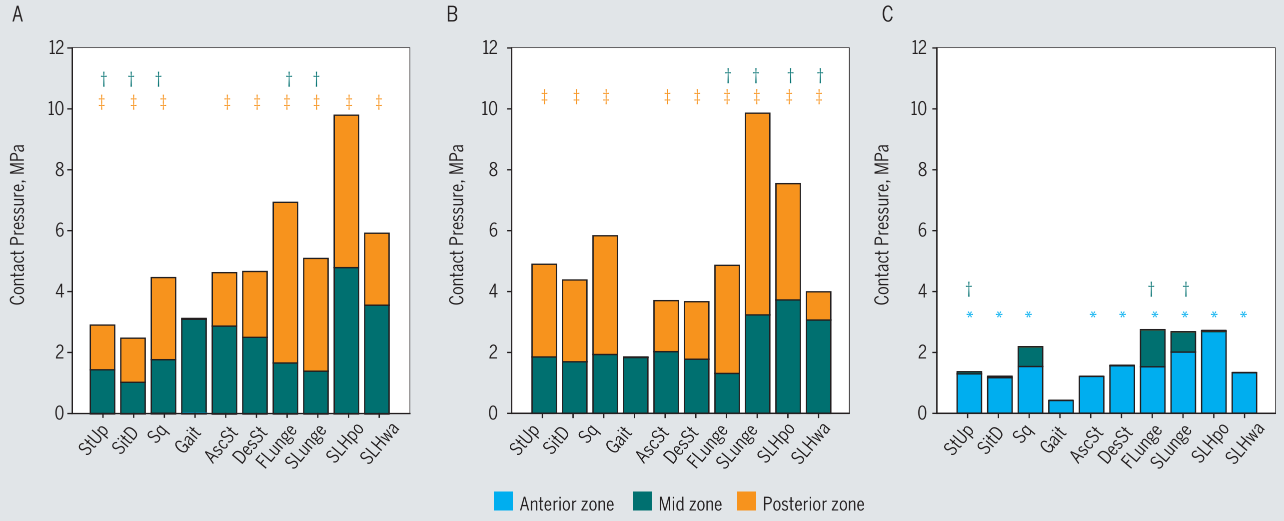

FIGURE 3. The average maximum tibiofemoral pressure on the anterior, mid, and posterior zones of the medial condyle (A) and lateral condyle (B). (C) The average maximum patellofemoral pressure on the anterior, mid, and posterior zones of the femur. Values are means. *Significant difference in anterior zone pressure compared to gait. †Significant difference in mid zone pressure compared to gait. ‡Significant difference in posterior zone pressure compared to gait. Bonferroni-corrected $\alpha = .0056$. Abbreviations: AscSt, ascending stairs; DesSt, descending stairs; FLunge, forward lunge; SitD, sit-down; SLHpo, single-leg hop push-off; SLHwa, single-leg hop weight acceptance; SLunge, sideward lunge; Sq, squat; StUp, stand-up.