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Short Communication

Comparison of two methods of determining patellofemoral joint stress during dynamic activities

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ABSTRACT

Background: Joint specific models rely on muscle force estimates to quantify tissue specific stresses. Traditionally, muscle forces have been estimated using inverse dynamics alone. Inverse dynamics coupled with static optimization techniques allow for an alternative method in estimating muscle forces. Differences between these two techniques have not been compared for determining the quadriceps force for estimating patellofemoral joint stress.

Methods: Eleven female participants completed five squats and ten running trials. Motion capture and force platform data were processed using both solely inverse dynamics and inverse dynamics with static optimization to estimate the quadriceps force in a patellofemoral joint model.

Findings: Patellofemoral joint stress calculations were consistently higher when using the combination of inverse dynamics and static optimization as compared to the inverse dynamics alone ($p < 0.05$) yielding estimates that were 30–106% greater.

Interpretation: When implementing joint models to estimate tissue specific stresses, the choice of technique used to estimate muscle forces plays an important role in determining the magnitude of estimated stresses in patellofemoral joint models.

1. Introduction

Mathematical models have been used to determine tissue stresses during movements to quantify the mechanical factors associated with injury [1–4]. To estimate patellofemoral joint stress (PFJS), knee extensor moments from inverse dynamics has been used to estimate quadriceps force (QF) [1,4,5]. Co-activation of muscles across the knee is rarely not included in the derivation of quadriceps force from these joint moments [i.e. 6]. However, one would anticipate that depending on the forces of other muscle groups, the net knee extensor moment may largely underestimate the QF used in these models.

The combination of inverse dynamics and static optimization can be used to estimate the force produced by individual muscles from multiple joint moments [7–9]. Because several knee muscles also cross the hip or ankle, such methods have the potential to estimate antagonist co-contraction [6]. We therefore expect that these different muscle force estimates may influence PFJS in typical movements. However, the magnitude of change is unknown.

Our aim was to compare differences in PFJS using the QF directly from the net knee moment from inverse dynamics (ID) and the QF from the combination of inverse dynamics and static optimization (IDSO) during squatting and running. Differences in PFJS between methods may aid in their interpretation.

2. Methods

2.1. Subjects

Eleven healthy females (22 ± 1.8 years; 169 ± 6.4 cm; 64.2 ± 4.9 kg) participated each with a Tegner score >5 [10] and no reported knee symptoms limiting activity. All provided their informed consent prior to testing approved by the Institutional Review Board.

2.2. Laboratory procedures

After a warm-up, participants completed 10 running trials between 3.52 and 3.89 m/s using a 20 m runway. Right foot contact

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occurred on a force platform flush with the floor (Model 4080, Bertec Corporation, Columbus, OH, USA) for each trial. Each then performed 5 weight-bearing squats with a foot on each force platform to a standardized 2s count where their thighs reached a point approximately parallel to the floor. Data were captured by 13 cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 180 Hz and force platforms at 1800 Hz. Forty-seven markers were placed on each participant's skin and/or tight fitting clothing [9]. Analog and kinematic data were filtered at 15 Hz and processed through the Human Body Model software (HBM, Motek Medical, Amsterdam, Netherlands) to obtain joint kinematics, kinetics, and muscle forces with static optimization.

2.3. Data analysis

For the ID method, the average quadriceps moment arm was calculated the average of the four quadriceps-element moment arms as a function of knee angle. The QF was then calculated by dividing the net knee extensor moment from inverse dynamics by the average quadriceps moment arm. QF was then used to calculate patellofemoral joint reaction force (PFJRF).

For the IDSO method, QF was a sum of the rectus femoris, vastus medialis, vastus lateralis, and vastus intermedius muscles from static optimization where 300 muscle tendon units were used based on a 44 degrees-of-freedom musculoskeletal model with 16 segments [9]. Muscle forces were estimated from the joint moments by minimizing a static cost function where the sum of squared muscle activations was related to maximum muscle strengths at each time step. Each quadriceps muscles moment arm (in meters) was described by polynomial equations within HBM as a function of knee angle where x is knee flexion angle (in radians):

$$\text{Rectus femoris(RF)} = 0.0519235 - 0.0064865x$$

$$\begin{aligned}\text{Vastus medialis(VMO)} = {} & 0.0434523 + 0.0059805x \\ & + 0.0089959x^2 + 0.0021733x^3\end{aligned}$$

$$\begin{aligned}\text{Vastus intermedius(VI)} = {} & 0.044273 + 0.0066606x + 0.0097213x^2 \\ & + 0.0022705x^3\end{aligned}$$

$$\begin{aligned}\text{Vastus lateralis(VL)} = {} & 0.0401728 + 0.0138364x + 0.0145048x^2 \\ & + 0.0033264x^3\end{aligned}$$

Forces from the individual quadriceps muscles were summed and used to estimate the PFJRF for the combined IDSO method.

The PFJRF was multiplied by a factor k from Brechter and Powers [1]:

$$k(x) = \frac{(4.62e^{-01} + 1.47e^{-03}x - 3.84e^{-05}x^2)}{(1 - 1.62e^{-02}x + 1.55e^{-04}x^2 - 6.98e^{-07}x^3)}$$

where x is the knee flexion angle. Hence,

$$\text{PFJRF}(x) = k(x) \times \text{QF}(x)$$

Patellofemoral joint (PFJ) contact area was calculated as a function of knee angle ($r^2 = 0.99$) using data by Connolly et al. [11] to formulate an equation as used previously [4] for running trials:

$$\text{Contact area}(x) = 0.0781x^2 + 0.6763x + 151.75$$

For squatting trials, Powers et al. [12] was used since the depth exceeded the knee flexion angles in Connolly et al. [11]. A cubic function was fit ($r^2 = 0.97$) to these data giving the following equation:

$$\text{Contact area}(x) = -0.0001x^3 - 0.0082x^2 + 3.5071x + 73.81$$

PFJS was then determined by:

$$\text{PFJS}(x) = \frac{\text{PFJRF}(x)}{\text{Contact area}(x)}$$

2.4. Statistical analysis

A multivariate analysis of variance determined differences between the two approaches for estimating mean PFJS variables separately for the squat and running using SPSSS 21 (IBM, Aramonk, NY, USA). Alpha was set to 0.05. Follow up univariates investigated differences in peak PFJS, stress time integral and QF for each movement.

3. Results

Multivariate analyses for the squat and running data yielded a Wilk's lamba of 0.031 ($p < 0.001$) and 0.012 ($p < 0.001$). Univariate analyses showed PFJS variables were consistently higher (30–106%) when using IDSO compared to ID alone ($p < 0.05$). Large effects were seen for all variables (Table 1). Large differences occurred in peak stress, integrated stress and peak QF when using the combination of IDSO to estimate QF. This was higher when hamstring and gastrocnemius forces were considered (Fig. 1). Using the net moment from ID to estimate peak QF resulted in lower stress.

Table 1
Means and standard deviations for discrete comparisons between techniques (inverse dynamics estimates of quadriceps force vs. inverse dynamics and static optimization estimates of quadriceps force) for the squat and running performances. pPFJS indicates the peak patellofemoral joint stress (MPa), PFJS·TI = patellofemoral joint stress time integral (MPa s) and pQF indicates the peak quadriceps force (BW).

	Inverse dynamics	Inverse dynamics and static optimization	Effect size	% Difference	*p*-value
Squat trials					
pPFJS	9.81 (sd 3.36)	17.06 (sd 4.34)	1.87	54.0	<0.001
PFJS·TI	7.51 (sd 1.98)	12.87 (sd 2.33)	2.48	52.6	<0.001
pQF	3.81 (sd 0.72)	5.16 (sd 0.82)	1.75	30.1	<0.001
Running trials					
pPFJS	7.53 (sd 1.02)	15.18 (sd 1.65)	5.58	67.4	<0.001
PFJS·TI	0.74 (sd 0.18)	1.41 (sd 0.24)	3.16	62.3	<0.001
pQF	3.12 (sd 0.69)	10.10 (sd 1.03)	7.91	105.6	<0.001

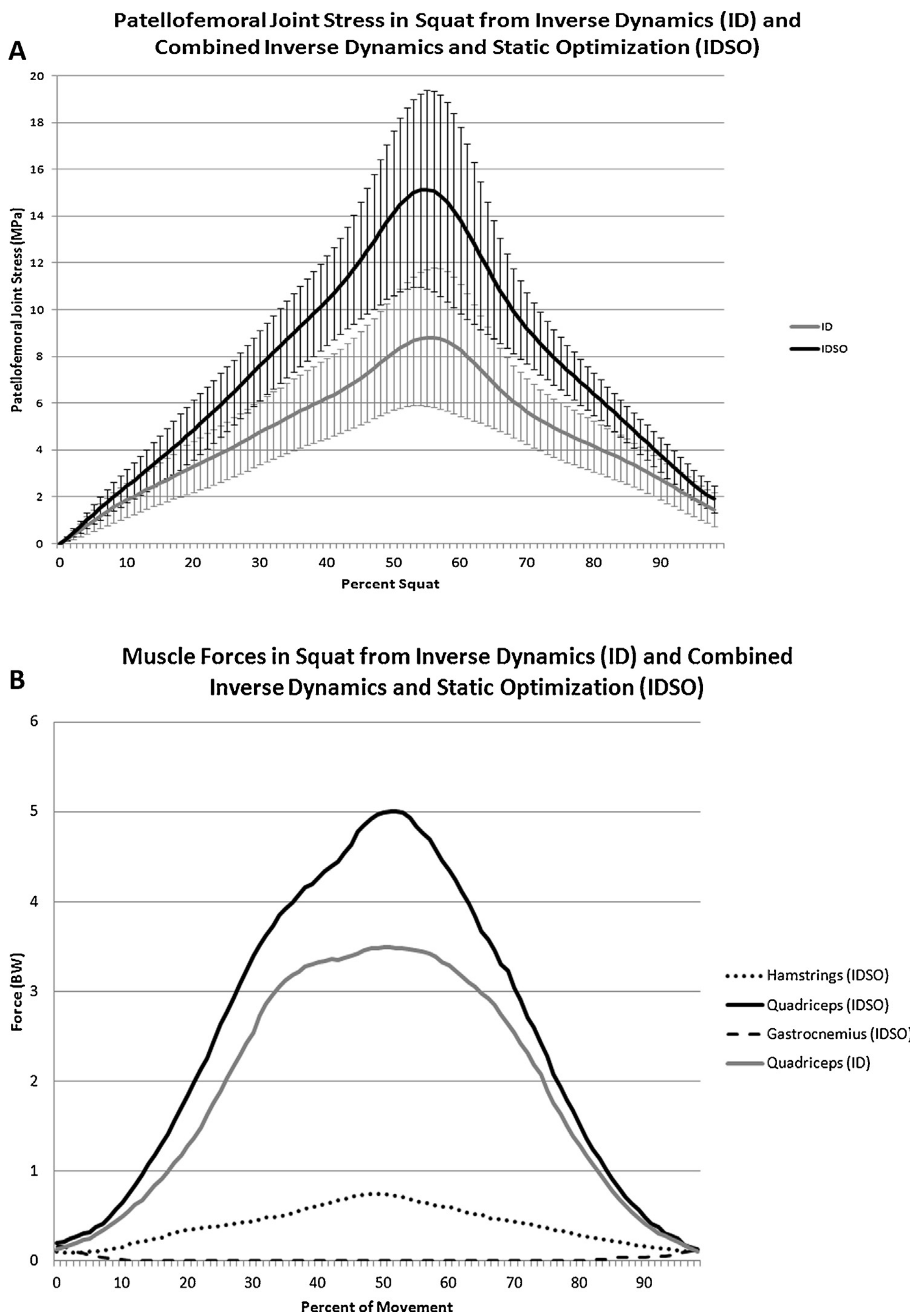

Fig. 1. (A) Ensemble averaged and time normalized curves for all participants (bold lines with standard deviation bars for patellofemoral joint stress) comparing patellofemoral joint stress based on inverse dynamics estimates of quadriceps muscle force (gray color) and the combination of inverse dynamics and static optimization to estimate quadriceps muscle force (black color) for each squat performance. (B) Ensemble averaged and time normalized curves for all participants for muscle force from inverse dynamics estimates of quadriceps muscle force (gray color) and individual muscle forces from the combination of inverse dynamics and static optimization to estimate muscle force (black color). The individual black lines represent the quadriceps force, hamstring force, and gastrocnemius force in Body Weight.

4. Discussion

Muscle force estimates from IDSO elicit greater PFJS than muscle force estimates from ID alone. The technique used to estimate muscle force appears to have a large influence on joint specific models. In making such comparisons across studies it appears important to note the technique used.

The magnitude of PFJS was much different when comparing the two techniques. The peak QF differed by 30–106%. During slower movement tasks such as squatting, the ID approach provides a closer representation of peak PFJS. Similarly, Isear et al. [13] reported minimal quadriceps/hamstring co-activation from electromyography during a weight bearing squat. This appears to agree with lower force estimates from the hamstrings and gastrocnemius shown in our data during the squat (Fig. 1).

Greater PFJS differences occurred with running while the magnitude of PFJS from solely ID was similar to previous work [2,4] where the QF was determined directly from the net moment. The greater difference in PFJS is due to the inability of the ID being able to account for co-activation of muscles

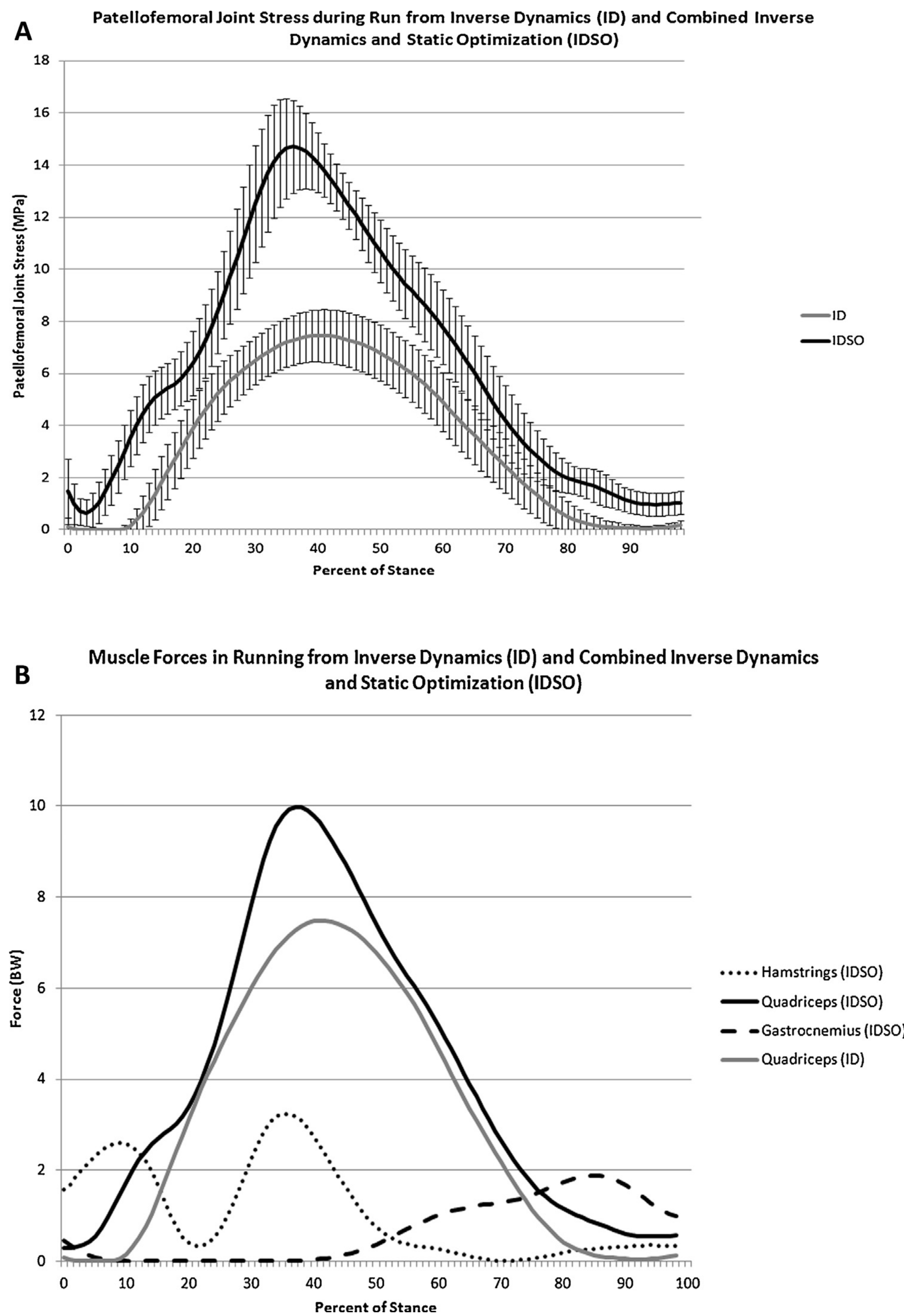

Fig. 2. (A) Ensemble averaged and time normalized curves for all participants (bold lines with standard deviation bars) comparing patellofemoral joint stress based on inverse dynamics estimates of quadriceps muscle force (gray color) and the combination of inverse dynamics and static optimization to estimate quadriceps muscle force (black color) for each running performance. (B) Ensemble averaged and time normalized curves for all participants for muscle force from inverse dynamics estimates of quadriceps muscle force (gray color) and individual muscle forces from the combination of inverse dynamics and static optimization to estimate muscle force (black color). The individual black lines represent the quadriceps force, hamstring force, and gastrocnemius force in Body Weight.

inherent in impact related activities such as running [14,15]. Hamner et al. [15] showed greater quadriceps/hamstring co-activation based on electromyography data and muscle force estimates from their simulations of running. Our average muscles forces shown in Fig. 2 with our data show a similar pattern.

Differences in PFJS between techniques reflect the magnitude of QF estimated. ID interprets muscle force contributions from a single joint while the combination of IDSO accounts for muscular contributions of muscles often crossing multiple joints. This is due to the load sharing, agonist–antagonist activity, biarticular muscle energy transfer and dynamic coupling associated with using the IDSO approach [8].

Limitations include the use of a two-dimensional PFJ model such that the PFJRF was directed posterior onto the femur. Although a difference in PFJS magnitude was shown, which approach yields a more accurate representation cannot be stated and remains an area of further research.

5. Conclusions

When implementing joint models to estimate tissue stress, the technique used to estimate muscle forces is critical in determining the magnitude of PFJS. Greater PFJS variables and peak QF occurred using the combination of IDSO than using ID alone due to inclusion of co-activating muscles crossing the knee joint.

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Conflict of interest statement

TWK and CNV have no conflict of interest with this work.

AJvdB received consulting fees for development of the Human Body Model software, which was used in the study, and may receive future royalties.

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