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Short communication

Sensitivity of subject-specific models to errors in musculo-skeletal geometry

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ABSTRACT

Subject-specific musculo-skeletal models of the lower extremity are an important tool for investigating various biomechanical problems, for instance the results of surgery such as joint replacements and tendon transfers. The aim of this study was to assess the potential effects of errors in musculo-skeletal geometry on subject-specific model results. We performed an extensive sensitivity analysis to quantify the effect of the perturbation of origin, insertion and via points of each of the 56 musculo-tendon parts contained in the model. We used two metrics, namely a Local Sensitivity Index (LSI) and an Overall Sensitivity Index (OSI), to distinguish the effect of the perturbation on the predicted force produced by only the perturbed musculo-tendon parts and by all the remaining musculo-tendon parts, respectively, during a simulated gait cycle. Results indicated that, for each musculo-tendon part, only two points show a significant sensitivity: its origin, or pseudo-origin, point and its insertion, or pseudo-insertion, point. The most sensitive points belong to those musculo-tendon parts that act as prime movers in the walking movement (insertion point of the Achilles Tendon: LSI=15.56%, OSI=7.17%; origin points of the Rectus Femoris: LSI=13.89%, OSI=2.44%) and as hip stabilizers (insertion points of the Gluteus Medius Anterior: LSI=17.92%, OSI=2.79%; insertion point of the Gluteus Minimus: LSI=21.71%, OSI=2.41%). The proposed priority list provides quantitative information to improve the predictive accuracy of subject-specific musculo-skeletal models.

1. Introduction

Accurate knowledge of lower limb muscle and joint reaction forces is fundamental to explore several biomechanical problems. Musculo-skeletal (MS) models have previously been used to simulate the effects of surgery such as joint replacements (Delp et al., 1994; Piazza and Delp, 2001) and tendon transfers (Piazza et al., 2003; Reinbolt et al., 2009). In these cases, subject-specific MS geometry is essential to achieve reliable musculo-tendon (MT) force predictions (Lenaerts et al., 2009). Unfortunately, it remains unclear which parameters and which muscles are most sensitive to potential errors.

Previous analyses on MS geometry focused on the sensitivity of muscle moment arms (Hoy et al., 1990; Maganaris, 2004; Out et al., 1996), whose estimation depends on the identification of MT path (Pal et al., 2007; Rohrle et al., 1984). However, to our knowledge no comprehensive analysis has been performed on complex, multi-segment MS models.

The aim of this study was to assess the potential effects of errors in MS geometry on subject-specific models outcome. We performed an extensive sensitivity analysis to quantify the effect of perturbation of muscle origin, insertion and via points on the model force predictions during gait. The results provided quantitative information to draw up a priority list of the points that need to be estimated most accurately, in order to obtain more reliable subject-specific MS models.

2. Methods

We used the Twente Lower Extremity Model (TLEM) (Klein Horsman et al., 2007) implemented in the AnyBody Modeling System ver. 4.2.1 (Damsgaard et al., 2006). The model consisted of 12 body segments, 11 joints, and 21 degrees of freedom (Fig 1a). Each leg contained 56 MT parts whose mechanical effect was described by 159 three-element, Hill type MT elements (Zajac, 1989). Each MT element was described by the origin and insertion points on the corresponding segments. In case of surrounding structures, such as retinacula and tendon sheaths, via points were defined (Delp et al., 1990). The most distal via point on the proximal segment, if present, was defined as pseudo-origin. Similarly, the most proximal via point on the distal segment, if present, was defined as pseudo-insertion.

Inverse dynamics simulations were based on 3D motion analysis and force-plate data recorded during a trial of walking on a level walkway. Age, height and mass of the one male subject were 26 years, 1.73 cm and 63 kg, respectively. The model was scaled in order to match the subject's anthropometry, derived from the marker positions relative to each other. A static optimization problem was solved,

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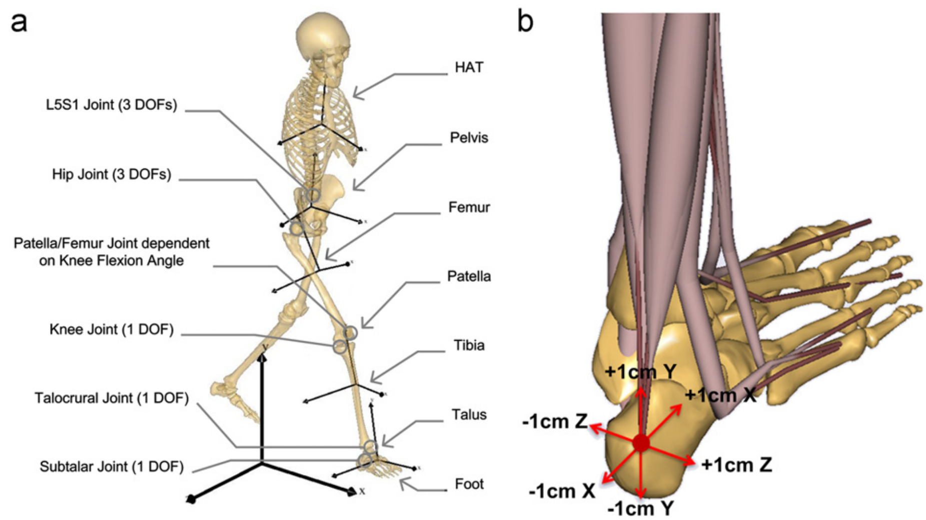

Fig. 1. (a) TLEM model. It consisted of 12 body segments: HAT (head, arms and trunk), pelvis, and right and left femur, patella, tibia, talus and foot. The fibula was considered as one unit in combination with the tibia. The model comprised 11 joints: L5S1 and left and right hip, knee, patella/femur, talocrural and subtalar. The L5S1 and hip joints were modeled as a ball-and-socket, defined by a rotation center and three orthogonal axes. The knee, talocrural and subtalar joints were defined as a hinge, with a fixed rotation center and axis. The patella could rotate with respect to the femur around a rotation axis with a fixed rotation center. The patellar tendon was defined as a non-deformable element that connected the patella to the tibia. Thus, without introducing an extra Degree of Freedom (DOF), the orientation and position of the patella depended solely on the knee flexion angle. The orientation and position of the center of mass of the pelvis with respect to a 3D global frame, together with the joint rotations of the L5S1, hip, knee, talocrural and subtalar joints, resulted in a model with 21 DOFs. (b) Perturbations of the 3D location of the insertion point of the Achilles Tendon from its nominal position. Perturbations of $+1$ cm and -1 cm were performed along the posterior/anterior (X), distal/proximal (Y) and medial/lateral (Z) directions of the local coordinate system of the foot.

minimizing the sum of the cubes of muscle activations at each time step (Crowninshield and Brand, 1981).

For each MT part, origin, insertion and via points were perturbed from their nominal position. For each point, 6 perturbations were applied: $+1$ cm and -1 cm along the posterior/anterior (X), distal/proximal (Y) and medial/lateral (Z) directions of the local segment coordinate systems (Wu et al., 2002) (Fig. 1a and b). MT parts sharing a common point were perturbed simultaneously (Fig. 1b). For reasons of symmetry, only the MT parts in the right leg were perturbed. In total, 55 origin points, 39 insertion points and 39 via points (including pseudo-attachment points) were perturbed from their nominal position, for a total of $(55+39+39)*6=798$ perturbations.

For each perturbed MT element, tendon slack lengths were automatically recalibrated maintaining the nominal optimal muscle fiber length. Then, a new static optimization problem was solved. Sensitivity of the model was quantified by computing two metrics:

1. Local Sensitivity Index (LSI), to quantify the effect of the perturbation on the predicted force produced only by the perturbed MT parts:

$$LSI = \frac{\sum_{i=pert} \int_0^T |F^{MT}_{new,i}(t) - F^{MT}_{old,i}(t)|\,dt}{\sum_{i=pert} \int_0^T F^{MT}_{old,i}(t)dt} 100\% \tag{1}$$

2. Overall Sensitivity Index (OSI), to quantify the effect of the perturbation on the predicted force produced by all the remaining not-perturbed MT parts of the right leg:

$$OSI = \frac{\sum_{i\neq pert} \int_0^T |F^{MT}_{new,i}(t) - F^{MT}_{old,i}(t)|\,dt}{\sum_{i\neq pert} \int_0^T F^{MT}_{old,i}(t)dt} 100\% \tag{2}$$

where $F^{MT}_{old,i}(t)$ and $F^{MT}_{new,i}(t)$ are the nominal and perturbed values of force, respectively, produced by the perturbed ($i=pert$) and not-perturbed ($i\neq pert$) MT parts at time step t, and T is the final time of the simulated gait cycle. Pilot results showed that perturbations in the right leg had no influence on predicted forces in the left leg.

For the three origin, insertion and via points that showed the highest OSI values, we also performed perturbations of -1.5 cm, -0.5 cm, $+0.5$ cm and $+1.5$ cm along the X, Y and Z directions, in order to check the linearity of the sensitivity values.

3. Results

This study indicated that the model predictions were sensitive to small changes in MS geometry. Tables A1, A2 and A3 show the sensitivity results for perturbations of muscle origin, insertion and via points, respectively.

LSI values, representing the sensitivity of the perturbed MT parts, depended strongly on which point was perturbed and on the direction of the perturbation (Figure 2a–c). Mean LSI values ranged from a maximum of 39.10% (insertion point of the Obturator Externus Superior (Table A2)) to negligible contributions for the least sensitive points. The maximal LSI value was equal to 80.89% (insertion point of the Obturator Externus Superior, $+1$ cm along the Y direction (Table A2)).

Similarly, OSI values, representing the sensitivity of the not-perturbed MT parts, depended strongly on which point was perturbed and on the direction of the perturbation (Fig. 2d). Mean OSI values ranged from a maximum of 7.17% (insertion point of the Achilles Tendon (Table A2)), to negligible contributions for the least sensitive points. The maximal OSI value was equal to 15.47% (insertion point of the Achilles Tendon, $+1$ cm along the Z direction (Table A2)).

Moreover, LSI and OSI values showed a small Pearson linear correlation coefficient ($r=0.3661$). Hence, the points that showed very high LSI values did not necessarily show very high OSI values (Fig. 3).

Finally, for the three origin, insertion and via points that were found to be the most sensitive, the OSI values showed a close-to-linear pattern in the range of perturbations between -1.5 cm and $+1.5$ cm (Figure A1).

4. Discussion

The purpose of this study was to assess the sensitivity of subject-specific models to potential errors in MS geometry. Similarly to Redl et al. (2007), we quantified the sensitivity of the model by computing two metrics. Local Sensitivity Index (LSI) quantified the reaction of the perturbed MT parts to maintain their nominal contribution to the joint moment, and depended mainly on the variation of the moment arms. On the other hand, Overall Sensitivity Index (OSI) quantified the reaction of all the not-perturbed MT parts to balance the different contribution to

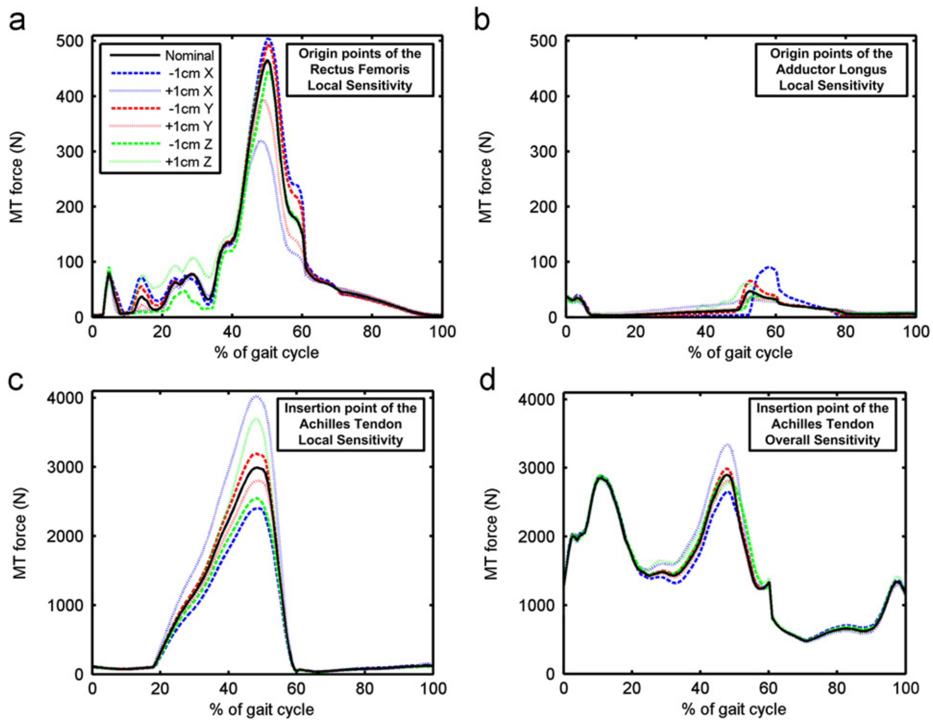

Fig. 2. Effect of perturbation of muscle points from their nominal position on the predicted MT forces during normal walking. Perturbations of +1 cm and −1 cm were performed along the posterior/anterior (X), distal/proximal (Y) and medial/lateral (Z) directions of the local segment coordinate systems. The black solid lines are the nominal MT forces before the perturbation; the blue, red and green dashed lines are the predicted MT forces after the perturbation along the X, Y Z directions, respectively. (a) Force produced by the Rectus Femoris after the perturbation of the origin points of the Rectus Femoris; (b) force produced by the Adductor Longus after the perturbation of the origin points of the Adductor Longus; (c) sum of the force produced by the Gastrocnemius Lateralis and Medialis, Soleus Lateralis and Medialis, and Plantaris after the perturbation of the insertion point of the Achilles Tendon; (d) sum of the forces produced by all the remaining not-perturbed MT parts after the perturbation of the insertion point of the Achilles Tendon. Local Sensitivity Index (LSI) was calculated by integrating the absolute difference between the nominal and perturbed MT forces over the simulated gait cycle, and then summing these integrated quantities across all the perturbed MT parts (see Eq. (1)). Overall Sensitivity Index (OSI) was calculated by integrating the absolute difference between the nominal and perturbed MT forces over the simulated gait cycle, and then summing these integrated quantities across all the non-perturbed MT parts (see Eq. (2)). Please note that different scales were used for subplots a, b and c, d. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

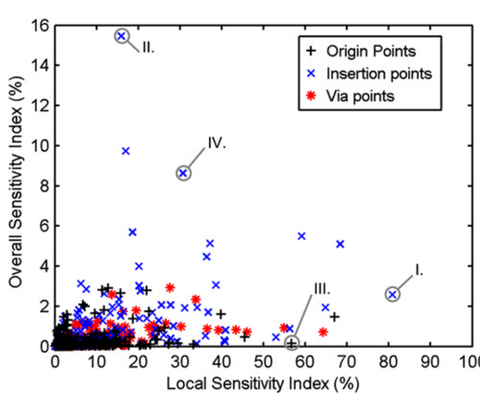

Fig. 3. Overall Sensitivity Index (OSI) values of the model to perturbations of muscle points from their nominal position, plotted against their relative Local Sensitivity Index (LSI) values. LSI and OSI values showed a small Pearson linear correlation coefficient (r=0.3661). The point that showed the highest LSI value (I: insertion point of the Obturator Externus Superior, +1 cm along the Y direction (Table A2)) differs from the point that showed the highest OSI value (II: insertion point of the Achilles Tendon, +1 cm along the Z direction (Table A2)); III: origin point of the Popliteus, +1 cm along Y direction showed very high LSI value but very low OSI value (Table A1); the insertion point of the Achilles tendon showed the maximal LSI value for perturbation of +1 cm along the X direction (II), while the maximal OSI value for perturbation of +1 cm along the Z direction (IV).

the joint moments by the perturbed MT parts, especially for biarticular MT parts.

For each MT part (the only exception was the Sartorius), only two points showed significant sensitivity: its origin, or pseudo-origin, point and its insertion, or pseudo-insertion, point. In fact, muscle moment arms were affected only by perturbations of attachment or pseudo-attachment points, while perturbations of any other point would just affect the length of the MT element.

Moreover, points showing high LSI values but low OSI values indicated large relative changes in MT parts contributing only little to the joint moments: the effect of the perturbation was limited to the perturbed MT part only and did not influence the rest of the model. On the contrary, high OSI values indicated MT parts with an important role during the gait and whose perturbation would affect the remaining MT parts.

For these reasons, we decided to use OSI values as an index to draw up a priority list of the points that need to be estimated most carefully to create a more reliable subject-specific MS model (Table 1). The most sensitive points belong to the MT parts that act as prime movers in the walking movement (Triceps Surae, Quadriceps Femoris, Hamstrings) and hip stabilizers (Gluteal Muscles, Iliacus, Obturator Internus and Externus, and Piriformis).

Several limitations should be kept in mind before interpreting our results. Firstly, the proposed sensitivity analysis was based on the gait simulation of a single subject. Gait simulations of various healthy subjects are likely to show great similarities in the force predictions. Therefore, the ranking of the most sensitive points is expected to remain similar.

Secondly, the sensitivity analysis was applied only to normal walking. Since muscle function strongly depends on the task performed (Liu et al., 2008), results are expected to change based on the movement analyzed (Scovil and Ronsky, 2006).

Thirdly, the static optimization problem was solved using a single performance criterion, specifically by minimizing the sum

Table 1
Priority list of the most sensitive attachment, or pseudo-attachment, points to perturbations from their nominal position. Perturbations of +1 cm and −1 cm were performed along the posterior/anterior (X), distal/proximal (Y) and medial/lateral (Z) directions of the local segment coordinate systems. For each point, mean values of Local Sensitivity Index (LSI) and Overall Sensitivity Index (OSI) over X, Y and Z direction and over the six perturbations are indicated. Cells shading (blue for LSI, red for OSI) is directly proportional to the OSI value. O., P.O., I. and P.I. indicate if the point represents an origin, pseudo-origin, insertion or pseudo-insertion, respectively.

		Local Sensitivity Index (%)				Overall Sensitivity Index (%)			
		X	Y	Z	**Mean**	X	Y	Z	**Mean**
Achilles Tendon	I.	24.62	5.60	16.46	**15.56**	7.17	1.74	12.60	**7.17**
Gluteus Medius Anterior	I.	15.94	28.39	9.43	**17.92**	3.31	3.62	1.42	**2.79**
Rectus Femoris	O.	18.89	10.70	12.08	**13.89**	2.72	1.74	2.86	**2.44**
Gluteus Minimus	I.	28.65	22.89	13.59	**21.71**	4.08	1.74	1.40	**2.41**
Gluteus Medius Posterior	I.	53.43	32.57	11.78	**32.60**	4.08	1.93	0.69	**2.23**
Obturator Internus	I.	21.08	37.22	6.65	**21.65**	1.51	3.92	0.88	**2.10**
Iliacus	I.	5.98	2.19	6.87	**5.01**	1.39	1.34	3.00	**1.91**
Quadriceps Femoris	I.	15.06	14.24	7.82	**12.37**	1.85	1.88	1.16	**1.63**
Peroneus Longus	P.O.	1.26	20.66	12.08	**11.33**	0.29	2.76	1.41	**1.49**
Obturator Externus Superior	I.	32.55	72.84	11.90	**39.10**	1.36	2.27	0.51	**1.38**
GluteusMediusAnterior	O.	6.94	2.91	1.58	**3.81**	2.05	1.20	0.39	**1.21**
Peroneus Brevis	P.O.	3.38	26.61	12.90	**14.29**	0.21	2.06	0.99	**1.09**
Sartorius	O.	2.56	1.31	2.62	**2.16**	1.53	0.63	1.02	**1.06**
Adductor Longus	O.	53.37	21.46	18.19	**31.01**	1.54	0.63	0.74	**0.97**
Piriformis	I.	14.59	22.67	5.00	**14.09**	0.55	1.55	0.67	**0.92**
Iliacus	P.O.	11.76	6.11	8.60	**8.82**	1.20	0.44	1.08	**0.91**
Gluteus Minimus Anterior	O.	20.68	2.12	3.10	**8.63**	1.56	0.38	0.53	**0.82**
Biceps Femoris	I.	24.53	15.47	10.58	**16.86**	1.08	0.79	0.51	**0.79**
Obturator Externus Superior	P.O.	25.68	19.46	9.87	**18.34**	1.01	1.00	0.33	**0.78**
Tibialis Anterior	P.I.	24.06	2.13	7.19	**11.13**	0.81	0.42	1.08	**0.77**
Obturator Internus	P.O.	3.82	5.05	2.77	**3.88**	0.56	1.06	0.29	**0.64**
Sartorius	I.	2.37	1.30	0.80	**1.49**	0.95	0.55	0.34	**0.61**
Soleus Medialis	O.	0.98	0.65	0.85	**0.83**	0.90	0.28	0.64	**0.60**
Semitendinosus	P.I.	16.22	13.27	7.34	**12.28**	0.85	0.51	0.36	**0.57**
Semimembranosus	I.	29.52	18.57	13.29	**20.46**	0.76	0.45	0.35	**0.52**
Soleus Lateralis	O.	0.62	0.61	1.21	**0.81**	0.78	0.20	0.50	**0.50**
Peroneus Tertius	P.O.	4.92	28.72	13.67	**15.77**	0.20	0.74	0.43	**0.46**
Flexor Hallucis Longus	P.O.	33.46	6.25	5.68	**15.13**	0.89	0.25	0.21	**0.45**
Biceps Femoris Caput Longum	O.	13.28	9.39	14.42	**12.36**	0.35	0.24	0.74	**0.44**
Tibialis Posterior Medialis	P.O.	9.38	45.71	5.64	**20.24**	0.23	0.90	0.17	**0.44**

of cubes of muscle activation at each time step. It is likely that sensitivity results depend on the performance criterion used, but the ranking of the most sensitive points could be similar for other criterions (De Groote et al., 2010).

In conclusion, this study showed that small errors in MS geometry can have a significant impact on muscle force predictions, and provided quantitative information to improve the predictive accuracy of MS models. An expansion of the proposed sensitivity analysis to several subjects and tasks, different performance criterion and other model parameters related to MS geometry and MT architecture could help to improve our understanding of the vulnerability of subject-specific models outcome to potential measurement errors.

Conflict of interest statement

The authors do not have any financial or personal relationships with other people or organization that could inappropriately influence their work.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2012.06.026.

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