MODELLING THE LOWER LIMB MUSCLES IN MUSCULOSKELETAL MODELS: A DISCRETISATION METHOD

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SUMMARY
Techniques of musculoskeletal modelling can be used for biomechanical investigations where direct in-vivo measurement of muscle forces is unfeasible. Modelling the musculoskeletal geometry involves the definition of muscle lines of action which influences the estimates of joint and muscle forces in simulations of motion. The study gives insight into the model capacity to reproduce the mechanical effect of the lower limb muscles on bones. The method is based on a previously published analysis of the muscles’ effect in a different anatomical district and it accounts for the joints’ range of motion (ROM). A comparison between a large and reduced muscle representation was performed to evaluate the errors on the mechanical effect. Furthermore full convergence curves of the exerted moments were calculated for increasing number of lines of action, addressing a methodological development for assessing the number of elements discretising the lower limb muscles.

INTRODUCTION
Computational models of the musculoskeletal system have been used to analyse several biomechanical problems [1]. It is common practice to discretise the muscles with one-dimensional actuators, however in the literature a wide range of number of lines of action modelling the lower limb muscles can be found [2,3]. Markedly different joint and muscle forces were predicted using different number of lines of action discretising the muscles [4,5]. A systematic study on a discretisation method was proposed only for the shoulder muscles [6], where a comparison of their mechanical effect (force and moment vectors) of a large and reduced muscle representation was performed in a reference skeletal pose. The results have been applied to the lower limb muscles [3] without demonstrating the validity for a different anatomical district. The aims of the present study are: first, to replicate the mentioned method [6] to the lower limb muscles to evaluate the errors between the 2 muscle representation in a reference pose, and extend it to the poses in the joints’ ROM; second, to extend the method to full convergence curves, calculating the resulting force and moment vectors for an increasing number of muscle lines of action throughout the ROM.

METHODS
Lower limb data of 2 cadaver specimens were obtained from detailed multiscale datasets [7] and publicly available at www.biomedtown.org. The datasets included the bone geometries, the points of the muscle attachment locations on bones, the superficial paths of the muscle fibres, muscle volumes and lengths. Data from different sources were loaded and spatially registered through a dedicated software (LHPBuilder, SCS, IT). The muscles attachment areas were subdivided according to shapes into points, straight or curved lines and surfaces. Each muscle was schematised by a combination of attachment shapes. A mathematical description of the muscle attachment areas was fitted to the data points using a least squares criterion (Matlab®, The MathWorks, Inc., USA). A map of muscle bundle distributions was used to locate an arbitrary large number of rectilinear elements (Fig.1).

Figure 1: Dataset and attachment areas modelling (16 lines of action shown) of a Gluteus Medius muscle

The mechanical effect of each muscle was described by the resulting force \( \mathbf{Y}_F \) and moment vector \( \mathbf{Y}_M \). Each muscle force was supposed to be uniformly distributed between the lines of action and proportional to the muscle physiological cross sectional areas (PCSA) and tension. The reference point for the calculation of the moment vectors was chosen to be the centroid of the attachment areas [6] and it was assumed 200 elements sufficient to correctly model the muscle mechanical effect (\( \mathbf{Y}_{200} \)). The generalized force vector was then calculated for a reduced number of elements (\( \mathbf{Y}_r \)) correspondent to the number of DOF influenced by the muscles (up to 6) [6]. In order to evaluate the errors between the large and the reduced representations, the absolute error \( e_a \) and relative error \( e_r \) on the moment vectors were calculated as follows:
In order to move the parts in any pose of the active joints’ ROM [8], a computational model of the skeletal system of the lower limbs was defined as a 7-segment, 10 DOF articulated system and generated for each cadaver specimen. The moment vectors were then calculated throughout the ROM to evaluate the errors between the 2 muscle representations. Furthermore, the moment vectors \( \mathbf{Y}_n \) were calculated for increasing numbers of muscle lines of action \( n \) throughout the ROM, thus the errors were evaluated between \( \mathbf{Y}_{200} \) and \( \mathbf{Y}_n \).

\[
e_a = \| \mathbf{Y}_{200} - \mathbf{Y}_r \|; \quad e_r = 100 \frac{\| \mathbf{Y}_{200} - \mathbf{Y}_r \|}{\| \mathbf{Y}_{200} \|}
\]

RESULTS AND DISCUSSION
The comparison between the representation of muscle moment vectors by a reduced number (up to 6) and a large number (200) of muscle lines of action shows absolute errors \( e_a \) over 1Nm for the Vastus Medialis, Gluteus Medius, Vastus Lateralis and Gluteus Maximus. For most muscles, \( e_a \) was comprised between 0.1 and 1Nm, and the other errors were below 0.1Nm (Fig. 2). Most muscles presented an average relative error \( e_r \) below 40%, excluding the muscles whose absolute moment contributes can be neglected. The comparison showed that the absolute errors were small except for broad attachment muscles with large PCSAs. This agreed with the previously published results [6], however the average relative errors were larger than those reported for the shoulder district (15%) [6].

![Figure 2: Comparison of muscle moments (average, min, max values): moments with large number of lines of action (\( ||\mathbf{Y}_{200}|| \)) and absolute errors between large and reduced muscle representations (\( ||\mathbf{Y}_{200} - \mathbf{Y}_r|| \))](image)

The comparison of the moments extended to the joints’ ROM showed slightly larger errors, implying a poor sensitivity to the ROM. For broad attachment muscles, a relevant sensitivity of the moment vectors to the musculoskeletal anatomy was found (Fig. 2).

All calculated moment values for the increasing number of lines of action converged to the moments for 200 lines, confirming that 200 elements constitute a good assumption to correctly reproduce the muscle mechanical effect (Fig. 3).

CONCLUSIONS
A discretisation method for the lower limb muscles was proposed, comparing their mechanical effect between a large and reduced muscle representation and calculating the convergence curves for an increasing number of lines of action. Larger absolute errors were found for broad attachment muscles according to a previous study [6], but larger average relative errors were found. A sensitivity of the exerted moments to the anatomy was found for broad attachment muscles, that seems to address to subject-specific muscle modelling. The calculated convergence curves can be used to address the adequate number of lines of action according to the biomechanics application.

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REFERENCES
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These convergence curves can be used to replicate the mechanical effect of the muscles on bones in biomechanics applications (e.g. FEM simulations).

![Figure 3: Convergence curves for a Vastus muscle in a pose in the joints’ ROM, showing muscle moments (\( M_x, M_y, M_z, ||M|| \)) and relative error for an increasing number of lines of action](image)