A general method to apply soft tissue wrapping constraints to muscle paths: Application to the ankle

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SUMMARY

Musculoskeletal models rely on accurate information regarding musculo-tendon paths, as they define muscle moment arms that are used in any calculation of muscle force. These paths are often approximated using digitised points so as to preserve only the vital information required to define musculo-tendon lines of action across and between limb segments. In some cases this results in only the muscle origin and insertion being defined, resulting in non-physiological muscle moment arm values being derived. The method presented here was a generic approach to account for wrapping surfaces when deriving muscle moment arms of a muscle, so as to constrain the absolute value to physiological bounds. This method was applied to the main flexor/extensor muscles of the ankle and moment arms were obtained and compared to previously measured values, with satisfactory results. The generic nature of the method presented here could be applied to other joints where a cylindrical wrapping surface is an acceptable approximation.

INTRODUCTION

One of the main purposes of musculoskeletal models is to predict muscle forces within a closed-chain system. This is commonly based on an individual muscle's moment arm about a joint, its maximum force generating capacity and the moment it is trying to balance. Therefore, accurate knowledge of musculo-tendon paths is required to calculate appropriate muscle forces and consequently joint contact forces. This is especially important near centres of rotation, where the musculo-tendon path dictates the muscle moment arms about the different axes of the joint. However, as most muscle geometry datasets are in the form of digitised points to represent the muscle-tendon path, this often results in complicated musculo-tendon paths being represented by only their origin and insertion, often neglecting any bony or soft tissue constraints that may be present. The result of this is often non-physiological musculo-tendon paths and moment arms, particularly when a straight line approximation is insufficient or incorrect. This is particularly important for muscles such as Tibialis Anterior or the Achilles tendon, where external and internal wrapping objects need to be imposed to maintain physiological moment arms. The aim of this work was to implement a simple, yet novel approach for defining soft tissue wrapping constraints in a musculoskeletal model of the ankle.

METHODS

A data set from the literature [1] was implemented in an ankle model, with muscle points scaled according to length and epicondylar width for the shank, and length for the foot. Cylindrical wrapping objects of different diameters were defined along the malleolar axis for each of the 7 muscle bundles, while muscle moment arms were calculated relative to the talocrural axis and functional joint centre.

The wrapping algorithm used 'via' points nearest the joint centre (if available, otherwise the origin and insertion) to define the initial line of action. The minimum distance between a point on this line of action and the wrapping object's axis was then found. If this point was on the correct side of the wrapping surface, it was considered to be physiological and used to calculate the muscle moment arm. If not, it was "pushed" to the surface of the cylinder in the sagittal plane. This point was checked to ensure it was on the correct side of the cylinder, otherwise it was pushed to the opposite side in the sagittal plane (Figure 1). For example, the muscle path for Tibialis Anterior would fall into the first case (correct side) and Tibialis Posterior would be an example of the second (incorrect side that required pushing across the cylinder).
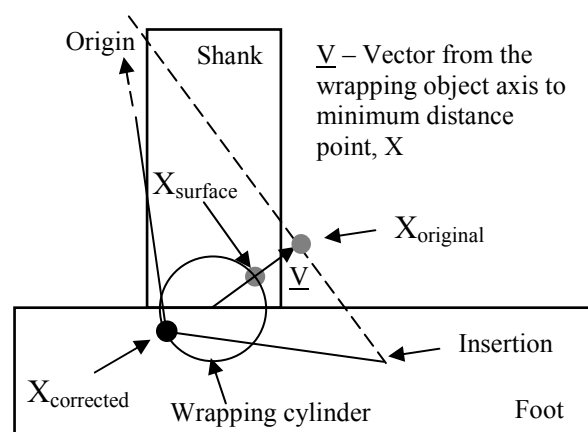

Figure 1: Illustration of the minimum distance point being "pushed" to the correct side of the wrapping object's surface for Tibialis Posterior. Dashed and solid lines denote the original and new muscle paths. Note: only one cylinder is shown here for clarity.

This wrapping point was then used to determine a new line of action for the muscle. The minimum distance between the

new lines of action and the joint centre in the proximal segment coordinate frame were then calculated and provided the muscle moment arms about all three rotational axes of the segment.

This method was then tested using retro-reflective marker data from an active heel drop exercise. This involved full weight-bearing on one leg and moving the weight-bearing ankle from maximum plantar-flexion to dorsi-flexion five times, with the metatarsal heads over the edge of a rounded step. The cycle used to test the method was selected because it had the largest change in flexion-extension angle.

RESULTS AND DISCUSSION

The results presented are flexion/extension moment arms during the heel-drop phase of the task (Figure 2). The "Achilles" moment arm was taken as the average of the Gastrocnemius, Soleus and Plantaris moment arms. Throughout the range of motion, the method was able to derive acceptable absolute moment arm values and ranges. Moment arms were found to range between 20 to 25mm, 20 to 26mm and 38 to 48mm for Tibialis Anterior, Peroneus Brevis and the Achilles tendon, respectively. Maximum moment arms for dorsiflexors of the foot were found to be in a dorsi-flexed position and vice versa for the plantar-flexors of the foot.
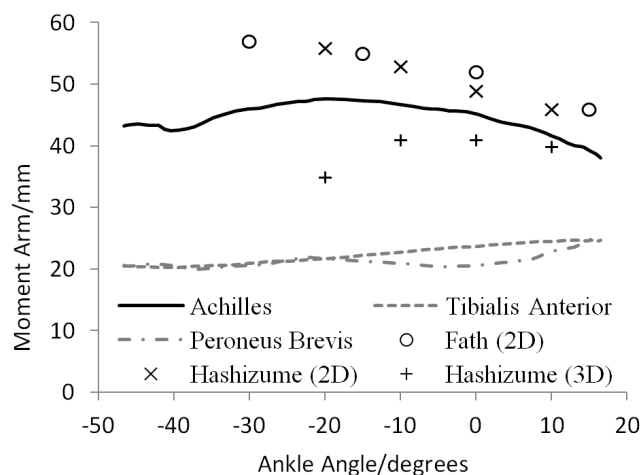

Figure 2: Relation between ankle flexion angle and muscle moment arms. Points from previous studies are for Achilles moment arms. A negative angle corresponds to plantarflexion.

A comparison to previous imaging-based measurements showed reasonable agreement in the range of moment arm values derived. Despite the absolute differences in moment arm values, the relative change in values were found to be similar to those reported previously for the Achilles tendon (26% increase here compared to 22% and 24% increases) [2,3]. However, as has been noted by others, there are inherent issues with imaging-based derivations of moment arms, which are highlighted by the differences obtained with

a 2D or 3D method [2]. Additionally, imaging-based approaches rely on user-input to define points to use in measuring muscle moment arms. In contrast to an imaging approach, a computational method to calculate muscle moment arms is a more objective approach to derive 3D muscle moment arms, as digitised bony landmarks are used to define segment coordinate frames and wrapping objects. Regardless of the methodology used to derive muscle moment arms, clarification should be made as to what they are relative to. This is of particular importance at the ankle, as use of the mid-point of the malleolar axis, a commonly used definition of ankle joint centre, results in inaccurate moment arm values, due to differences between the functional joint centre and this point. For other joints where the wrapping surfaces are not centred around axes defined by bony landmarks, this should also be clearly stated. This would allow for a more appropriate comparison of subsequent modeling outputs, such as muscle and joint contact forces, between different musculoskeletal models. Limitations of this approach are due to the simplification of wrapping to a single point on the wrapping surface. This may have implications for muscles that do not simply pass over or around the wrapping object, but have a significant amount of travel along it. The use of a single wrapping point could also affect the calculated musculo-tendon length changes and lines of action. Small changes in muscle moment arm values could have large implications for joint contact forces when considering functional muscle groups. In the case of the ankle plantar-flexors, this could result in a larger moment arm for each of the muscles, as the functional joint centre lies anterior to the malleolar axis. This would result in lower muscle force predictions for all ankle plantar-flexors and as such result in a lower overall peak contact force. This potentially significant change in joint contact force highlights the importance of accurate muscle moment arm values in musculoskeletal models.

CONCLUSIONS

The method presented here was a generic approach to account for wrapping surfaces when deriving muscle moment arms of a muscle, so as to constrain the absolute value to physiological bounds. This method was applied to the main flexor/extensor muscles of the ankle and moment arms were obtained and compared to previously measured values, with satisfactory results. The generic nature of the method presented here could be applied to other joints where a cylindrical wrapping surface is an acceptable approximation.

REFERENCES
1. Klein Horsman MD, et al., *J Clin. Biomech*, **22**: 239-247, 2007
2. Fath F, et al., *J. Appl. Physiol*, **109**: 1644-1652, 2010.
3. Hashizume S, et al*., J. Biomech*, **45**: 409-413, 2012.