Journal of Biomechanics 92 (2019) 178–180

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech

Letter to the Editor

A commentary on Kalkman et al.'s letter to the editor regarding Alexander et al. (2019): "Children with cerebral palsy have larger in-vivo and linearly scaled Achilles tendon moment arms than typically developing children"

We are thankful for the opportunity to expand upon our research, which is to improve model specificity of Achilles tendon moment arm (AT MA) parameters for paediatric and paediatric cerebral palsy (CP) populations (Alexander et al., 2017, 2019). Due to space, readers are referred to the validated 3D *in-vivo* AT MA method developed by Alexander et al. (2017), which forms the foundation of the work presented in Alexander et al. (2019).

As correctly pointed out by Kalkman et al., there are limitations and delineations that prevent research (Alexander et al., 2017, 2019) from being directly compared between studies, and from being ubiquitously applied to heterogeneous paediatric and/or paediatric CP populations. We also agree with Kalkman et al., though a contributing factor, differences in participant characteristics between research studies are ancillary factors contributing to the contradictory AT MA length differences between studies (Kalkman et al. 2017; Alexander et al., 2019). Instead, the observed AT MA length differences between paediatric CP populations (not typically developing paediatric populations) within each study are likely attributed to the modelling assumption and limitations of each AT MA method. Rather than focusing this communication on comparing and contrasting specific modelling differences between an established 2D AT method (Kalkman et al. 2017) and a valid 3D *in-vivo* AT MA method (Alexander et al., 2017), our goal is to highlight the global differences between these methods, which we hope will help guide and progress future researcher within this important research area (i.e., paediatric CP and ankle joint & muscuolotendon modelling).

The accurate estimates of muscle forces are reliant on accurate AT MA estimates, which are non-linearly influenced by four interconnected musculoskeletal modelling parameters: (1) musculotendon properties (e.g., fibre length, tendon slack length, etc.), (2) musculotendon geometry (e.g., insertion points, volume, etc.), (3) bony morphology (e.g., shape, deformities etc.) and (4) joint geometry (i.e., axes, degrees of freedom, condylar surface, etc.). Unique to the ankle joint, the shank (i.e., parent body) rotates about the talus (i.e., child body), which is difficult to locate with surface anatomy, and cannot be measured with standard motion capture systems. Modelling workarounds to this problem is for researchers to use indirect methods to define the anatomical coordinate system of the talus body, which have downstream effects on ankle joint kinematic and AT MA estimates. Some indirect modelling methods include but are not limited to regression methods guided by anatomical landmarks or function joint centre and axes methods (Besier et al., 2013).

The tendon excursion (TE) method (and other 2D approaches) used by Kalkman et al. (2017) to estimate AT MA lengths is computationally comparable to function axes methods, but built upon the assumption that the joint under assessment functions as a hinge through its full range of motion (e.g., elbow) (An et al., 1984). Looking to previous literature, it is apparent that a 2D TE modelling approach, and its assumptions, are appropriate when estimating AT MA lengths among healthy and typically developing paediatric populations. Among healthy adult populations, there is much consistency between AT MA estimates when using 2D methods and the majority of 3D *in vivo* AT MA methods through the typical ankle dorsi/plantar flexion range (Fig. 1) (Fath et al., 2010; Maganaris et al., 2000; Hashizume et al., 2012; Sheehan, 2012; Rugg et al., 1990; Clarke et al., 2015). Among typically developing paediatric populations, Kalkman et al. (2017) and Alexander et al., (2019) reported equivalent normalised AT MA lengths when using 2D TE (15 ± 1.5%) and 3D *in vivo* (15 ± 1.2%) methods respectively. Interestingly, and in disagreement with our proposed hypothesis (Alexander et al., 2019), differences in normalised AT MA lengths between the 2D TE and 3D *in vivo* AT MA methods were only observed among paediatric CP populations. These results suggest that the modelling assumptions and limitations associated with the 2D TE method (An et al., 1984) may not be appropriate paediatric CP populations, which are known to have complex and varied musculoskeletal abnormalities. As correctly stated by Kalkman et al., and originally discussed in our manuscript (Alexander et al., 2019), one would expect to observe larger, not smaller moment arms if a 2D method, free of errors and assumptions was used to measure AT MA in 3D. Though an interesting discussion point, we stand by our results, but do concede that future research comparing 2D and 3D methodologies among paediatric CP populations is warranted.

In the context of musculoskeletal modelling, the exception to the rule is the rule when estimating the modelling parameters of paediatric CP populations. Therein, when possible, it is important that direct measures of CP populations' musculotendon properties, musculotendon geometry, bony morphology and joint geometry be obtained for the robust and reliable estimates of musculoskeletal model parameters like AT MA lengths among healthy, typically developing and pathological populations. Using Occam's razor principle, the most proficient method(s) to obtain direct, *in-vivo* measures of the musculoskeletal system is medical imaging (i.e., 3D ultrasound, CT, MRI etc.). Though time, cost and computational restrictions have limited the integration of medical imaging within standard motion capture and musculoskeletal modelling frameworks, it is the next frontier for the field of musculoskeletal modelling to overcome if it is to continue to add value to clinical best practice research and decision making.

The research by Alexander et al. (2019) is a small component of an evolving medical imaging informed motion capture and

https://doi.org/10.1016/j.jbiomech.2019.04.047

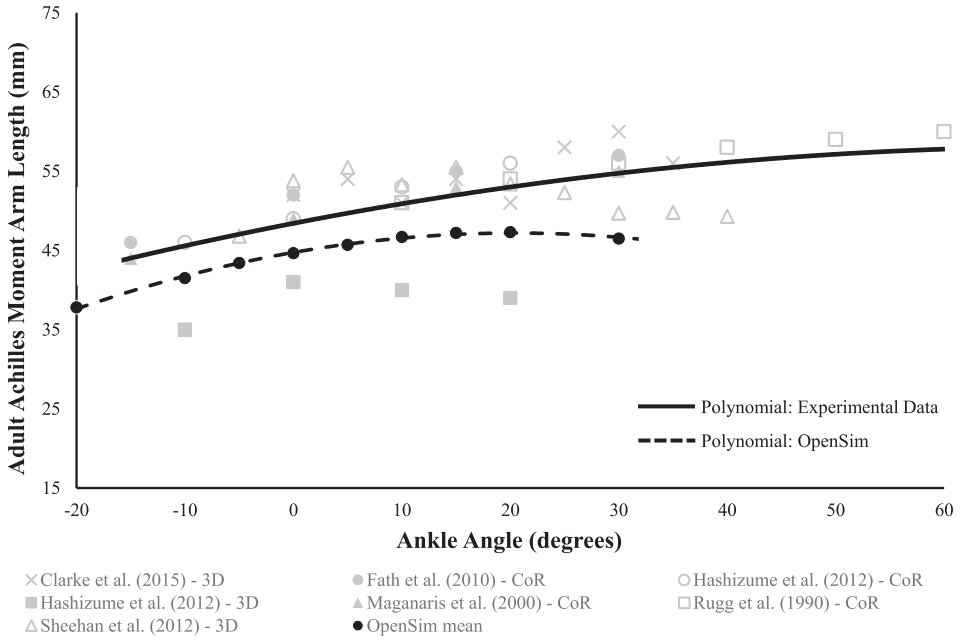

Fig. 1. Adult AT MA length measures from a mixture of literature using 2D and 3D *in-vivo* AT MA methods (grey data points). Mean adult AT MA lengths modelled in OpenSim (black data points) (Arnold et al., 2010; Delp et al., 2007). Experimental data was from five healthy adult male and three healthy adult females (22 ± 4.3 yrs, 1.8 ± 0.10 m and 75 ± 11.7 kg). The experimental procedures used to obtain the modelled AT MA lengths were approved by the University of Western Australia and University of Notre Dame Australia Human Research and Ethics Committees (RA/4/3/1562 & 012038F). A polynomial was fit to the experimental adult AT MA length measures from −15 to 60 degrees of angle dorsi/plantar flexion, which was parabolic in shape. A polynomial was fit to the adult AT MA lengths modelled in OpenSim from −20 to 30 degrees of angle dorsi/plantar flexion, which was also parabolic in shape. Image adapted from Alexander et al. (2017).

musculoskeletal modelling framework, which we hope will continue to progress with future research. Specifically, Alexander et al. (2017, 2019) has developed a reliable 3D *in-vivo* AT MA method and modelling framework for adult, paediatric and paediatric CP populations with fixed or limited ankle range of motion, during non-weight bearing conditions. As illustrated in Fig. 1, current open-source musculoskeletal models accurately estimate AT MA lengths across the typical dorsi/plantarflexion range of healthy adult populations (Arnold et al., 2000; Arnold et al., 2010; Delp et al., 2007). With continued medical imaging and musculoskeletal modelling advancements, we hope to see valid 3D *in-vivo* AT MA methods and modelling frameworks for all joints, joint degrees of freedom, movement phases' (stance vs. swing), movement tasks (high and low velocity) and populations (healthy/typically developing and pathological).

Expanding upon the nice CP and ankle-centric modelling recommendations made by Kalkman et al., in their letter to the editor: robust, reliable experimental 3D *in-vivo* AT MA methods with complimentary modelling frameworks need to be developed for individuals across (1) the lifespan, and (2) the pathological spectrum. In that, 3D *in-vivo* AT MA methods need to be integrated within standard motion capture and modelling frameworks for healthy or typically developing (a) paediatric, (b) adolescent, (c) adult and d) elderly populations. These medical imaging and modelling frameworks must also be built so that they can accommodate a wide range of pathological populations that: (i) can and cannot ambulate (weight bearing and non-weight bearing), (ii) can and cannot move through typical ranges of motion and (iii) present with or do not present with musculoskeletal abnormalities.

Declaration of Competing Interest

The authors disclose that they have no perceived or actual conflicts of interest associated with the proposed research.

Acknowledgements

The authors would like to thank Dr Luke Hopper from the University of Notre Dame for providing Achilles tendon moment arm model parameter data for use in Fig. 1.

Funding

The authors have not received any external funding for the publication of this work.

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Accepted 27 April 2019