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LETTER TO THE EDITOR

Comments on Harkness-Armstrong et al. (2021) 'In vivo operating lengths of the gastrocnemius muscle during gait in children who idiopathically toe-walk'

The article by Harkness-Armstrong et al. (2021a) analysed gastrocnemius fibre operating ranges during gait in children diagnosed as idiopathic toe walkers (ITWs) and in typically developing (TD) children. The ITWs were shown to walk with higher plantarflexor fibre lengths when compared with TD children. Moreover, the results showed that the plantarflexors of both ITW and TD children operated at fibre lengths above the optimal length during gait.

The reported findings are of interest because additional understanding of the functional musculotendon adaptations in ITWs might inform improved clinical management. The experimentally derived maximum moment–length curve informed the estimation of optimal gastrocnemius fibre lengths for both groups (Figure 2b of Harkness-Armstrong et al. (2021a)), and when normalised to this value, the results suggested that both groups used fibre lengths above optimal during the stance phase of the gait (Figure 2c of Harkness-Armstrong et al. (2021a)). This is a contentious finding that requires consideration. Indeed, as displayed in figure 3 of the paper by Harkness-Armstrong et al. (2021a) and acknowledged in the discussion, the gastrocnemius lateralis was not maximally activated at all joint angles during isometric testing. Furthermore, moment arm variation across ankle joint range of motion (McCullough et al., 2011) was not considered in determining the optimal fibre length.

The authors hypothesised that the abovementioned deficit in muscle activation observed during maximal voluntary contraction tasks might have led to an underestimation of optimal fibre length. To test this hypothesis, we simulated the experiment from Harkness-Armstrong et al. (2021a) using a neuromusculoskeletal model to re-evaluate the muscle operating range during gait.

To do so, we created a pathology-specific contracture model for ITWs by implementing a musculotendon contracture in a generic musculoskeletal model (Delp et al., 1990) that was simplified to include only a lumped gastrocnemius and a soleus muscle as plantarflexors (Veerkamp et al., 2021). The model is described in more detail by Veerkamp et al. (2021) and previously performed well in predictive simulations of gait, showing a good match with experimental data of a healthy gait. The model was scaled to the average height and weight of the ITWs (i.e., 1.38 m and 45.2 kg) from Harkness-Armstrong et al. (2021a) using the OpenSim scaling tool (Delp et al., 2007; v.3.3).

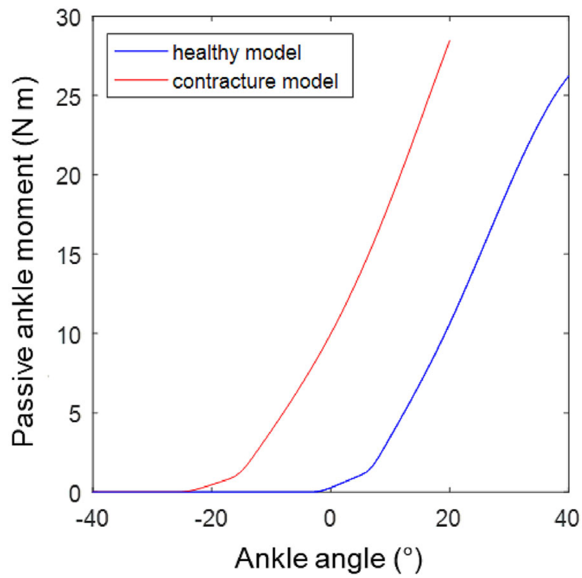

FIGURE 1 The passive ankle moment–ankle angle curve for the healthy, default model and for the pathology-specific contracture model representative for idiopathic toe walkers, with a shift of 20°. For the contracture model, the optimal fibre lengths and tendon slack length were obtained by minimising the root mean square error between the gastrocnemius and soleus passive moment–angle curve of the model and the 20° shifted curve

Musculotendon parameters were initially scaled such that the original force–length curves were maintained (Modenese et al., 2016). Next, for ITWs the generic passive ankle moment–angle curves for the gastrocnemii and soleus were shifted by 20° into plantarflexion (Figure 1), because the maximum passive dorsiflexion range in ITWs was ∼20° smaller than for TD children (Harkness-Armstrong et al., 2021b). To obtain ITW-specific muscle model parameters (i.e., optimal fibre lengths and tendon slack lengths) that best represented this shifted ITW curve, optimisation (*fmincon* in Matlab, 2016a; The MathWorks, Natick, MA, USA) was used. Obtained parameter values are presented in Table 1.

Measured joint angles and normalised EMG values at each joint angle were extracted from the paper by Harkness-Armstrong

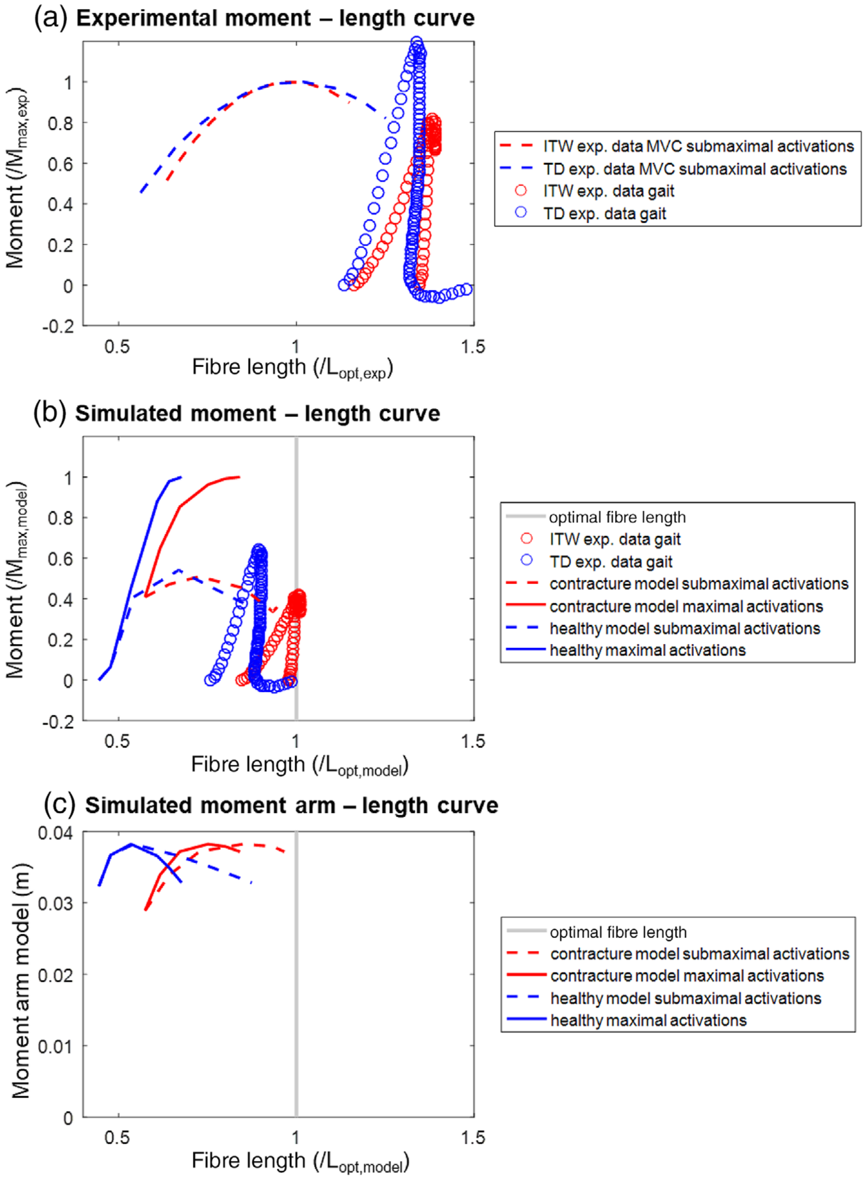

FIGURE 2 (a) The moment–length curve during maximal voluntary contractions with submaximal activations (dashed lines) and during gait (circles), extracted from the paper by Harkness-Armstrong et al. (2021a), suggesting that the plantarflexors from idiopathic toe walkers (ITW; red) and typically developing (TD) children (blue) operate at fibre lengths above the optimal lengths during gait. (b) The modelled moment–length curves and ITW-specific model with contracture (ITW; red) and with a healthy model (TD; blue), with submaximal activations based on EMG derived from Harkness-Armstrong et al. (2021a; dashed lines), and with maximal activations (continuous lines), suggesting how maximal activations at each ankle angle could have affected the experimentally found moment–length curve and optimal fibre length. (c) The gastrocnemius moment arm–length curves for the ITW-specific model with contracture (ITW; red) and the healthy model (TD; blue), with submaximal activations based on EMG derived from Harkness-Armstrong et al. (2021a; dashed lines) and with maximal activations (continuous lines), providing insight into the variation of moment arm over the range of motion of the ankle. Moment arm maximums were reached at fibre lengths below optimum

TABLE 1 Plantarflexor musculotendon parameters from the default model and from the pathology-specific model with a plantarflexor contracture representative for idiopathic toe walkers

Muscle	Parameter	Healthy model	Contracture model
Gastrocnemius	Tendon slack length (m)	0.30	0.26
	Optimal fibre length (m)	0.046	0.075
Soleus	Tendon slack length (m)	0.19	0.15
	Optimal fibre length (m)	0.038	0.068

et al. (2021a) using WebPlotDigitizer (https://automeris.io/WebPlotDigitizer; v.4.4) and used as inputs into the ITW model. Using the OpenSim-Matlab Application Programming Interface (API), the ankle angles of the healthy model and the ITW model with contracture were set to the extracted angles. At each angle, the plantarflexors were activated by the corresponding extracted EMG value to obtain a similar moment–length curve to that in the paper by Harkness-Armstrong et al. (2021a). This simulation experiment was then repeated by applying maximal activation of the plantarflexors. Furthermore, moment arm–fibre length curves were extracted from the model, Additionally, experimentally measured moment–fascicle length curves during gait were extracted from the paper by Harkness-Armstrong et al. (2021a).

When replicating the moment–length curves from Harkness-Armstrong et al. (2021a; Figure 2a) using simulations with maximum activations at all joint angles, the moment–length curves did not reach a descending limb and stayed below optimal fibre length (Figure 2b). This was caused by moment arms being maximal at fibre lengths below the optimal fibre length (Figure 2c). Indeed, previous research has shown that the Achilles tendon moment arm is maximal at a neutral ankle angle and decreases with increased dorsiflexion (McCullough et al., 2011), hence with increased fibre lengths.

After converting the measured moment–length curve during gait (Harkness-Armstrong et al., 2021a), the plantarflexors operated at values up to 1.01 optimal fibre lengths (Figure 1b). Hence, our simulation results showed that the plantarflexors operate on the ascending limb and plateau region of their force–length curves during gait. This result is in agreement with experimental studies of typical gait (Panizzolo et al., 2013; Rubenson et al., 2012). This operating range is also thought to increase the stability of the muscles by being more resistant against external perturbations and stretch damage (Morgan, 1990).

The model used in this letter has some limitations regarding simplifications of the muscle geometry and musculotendon model. A scaled generic, cadaver-based model was used, in which only the tendon slack length and optimal fibre length were adjusted to implement the contracture. Although the contracture implementation could not be validated, it was informed by the measured limitation in ankle dorsiflexion in ITWs. Also, the finding of increased muscle fibre length and reduced tendon length agrees with experimental findings (Harkness-Armstrong et al., 2021b). To evaluate the effect of our optimised contracture model, we repeated our analysis by shortening tendon slack length only, without changing optimal fibre length. The same findings were reproduced, with ITWs operating at values up to 1.01 optimal fibre length. Also, other musculotendon parameters in the model have not been validated in children. Ideally, these would be validated by performing experiments combining ultrasound, torque and joint angle measurements, in both passive and maximally active conditions. However, as also shown by the original paper, these types of experiments are difficult to perform in children, especially in ITWs.

Therefore, this simulation experiment demonstrates a proof of concept of how modelling can complement in vivo experiments and enhance data interpretation, because it enables simulation of experimental variables that are difficult to measure in vivo. Although the experimental results from Harkness-Armstrong et al. (2021a) might suggest that the gastrocnemius functions at lengths above optimum, our simulation results indicate that this is likely not to be the case.

AUTHOR CONTRIBUTIONS

Kirsten Veerkamp: Conceptualisation; analysis; funding; methodology; software; visualisation; writing (draft preparation and review/editing). Marjolein van der Krogt: Conceptualisation; funding; supervision; writing (review/editing). Niels Waterval: Writing (review/editing). Thomas Geijtenbeek: Software; writing (review/editing). Henry Walsh: Writing (review/editing). Jaap Harlaar: Conceptualisation; supervision; writing (review/editing). Annemieke Buizer: Writing (review/editing). David Lloyd: Conceptualisation; supervision; writing (review/editing). Christopher Carty: Conceptualisation; funding; supervision; writing (review/editing).

CONFLICT OF INTEREST

None declared.

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