IN VIVO RELATIONSHIP BETWEEN JOINT STIFFNESS, JOINT-BASED ESTIMATES OF MUSCLE STIFFNESS, AND SHEAR WAVE VELOCITY

[1] Andrew D. Vigotsky, [2] Elliott J. Rouse, and [1] Sabrina S.M. Lee

[1] Northwestern University, Evanston, IL, USA
[2] University of Michigan, Ann Arbor, MI, USA
email: vigotsky@u.northwestern.edu

INTRODUCTION

The underlying properties governing human joint mechanics, such as stiffness, are constantly regulated for effective, safe, and efficient interactions with the external environment. Joint stiffness (k_{joint}) is, in part, determined by the properties of the muscles surrounding the joint. The muscle-joint relationship can be thought of hierarchically, since there exists a lower level, muscle, and a higher level, joint. In light of this hierarchy, investigators often assess joint properties to make inferences about muscle-level changes. However, such approaches lack the specificity needed to understand the role of individual muscles.

Shear wave ultrasound elastography—which measures the velocity at which shear waves travel through tissue—has been increasingly used to assess the mechanical properties of muscle [2]. However, how shear wave velocity (SWV), measured at the muscle level, relates to k_{joint} and muscle stiffness *in vivo* remains poorly understood [2, 3]. Therefore, the purpose of this work was to quantify the relationships between 1) SWV of individual primary plantar flexors and ankle k_{joint}, and 2) SWV and joint-based estimates of muscle stiffness (k_{muscle}) in two muscles, medial gastrocnemius (MG) and soleus (SOL).

METHODS

Ten healthy, young adults (6 females, 4 males; age = 26 ± 4 years; body mass = 69 ± 16 kg; height = 171 ± 10 cm) participated in this study, which was approved by the Northwestern University Institutional Review Board. Ankle k_{joint}, SWV_{MG}, and SWV_{SOL} were measured in two positions (knee flexed, 90°; knee extended, 0°) and at three activation levels (0%, 20%, and 40% of maximum voluntary contraction, MVC) on two separate days. The ankle was positioned at 90° for all trials. The two knee positions permitted independent investigation of the MG, a bi-articular muscle, and the SOL, a uni-articular muscle.

Joint stiffness was measured using a custom dynamometer, by recording joint moment responses to 1° perturbations, collected over 27, 10-second trials for each activation. System identification analyses were used to isolate stiffness contributions to the ankle joint's resistance to rotation [4]. This approach differs from calculating the slope of the moment-angle curve, such that the measures are not strictly a function of the net moment demands of the task and are robust to inertial and damping components [1, 5]. Shear wave velocity was measured from the MG and SOL over six isometric trials for each condition (Aixplorer SuperSonic Imagine, Aix en Provence, France).

A biomechanical model was used to estimate k_{muscle} (Fig. 1). The ankle joint was modeled as a pin joint with two springs (k_{muscle} and k_{tendon}) acting in series about its center of rotation. Literature values for moment arm were used [6, 7], and k_{tendon} was measured experimentally by tracking the MG muscle-tendon junction with B-mode ultrasound during ramp (0–60%MVC), isometric contractions.

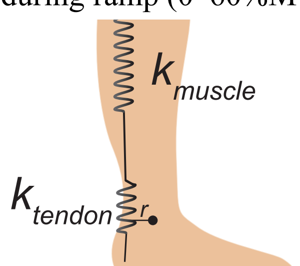

Figure 1: Biomechanical model to estimate muscle stiffness.

To understand the relationships between 1) SWV and k_{joint}, and 2) SWV and k_{muscle}, hierarchical linear statistical models were used. Trials were nested within participants, such that all relationships were within-subject.

RESULTS AND DISCUSSION

A strong, linear relationship was found between SWV_{MG}, SWV_{SOL}, and k_{joint} ($R^2 = 0.96$; RMSE = 14.6 N·m/rad) (Fig. 2A). SWV_{SOL} (when controlling for SWV_{MG}) had a greater slope in its relationship with k_{joint} than SWV_{MG} (when controlling for SWV_{SOL}). For example, if SWV_{SOL} and SWV_{MG} are 9 and 3 m/s, then $k_{joint} \approx 211$ N·m/rad. However, the inverse produces $k_{joint} \approx 113$ N·m/rad. Low collinearity between SWVs ($r = -0.331$) suggests that SOL and MG were independent regressors.

Shear wave velocity in both SOL and MG increased with ankle joint moment (Fig. 2B and C, $R^2 = 0.88$, $R^2 = 0.95$, respectively). The difference in slopes between flexion and extension in SWV_{MG} but not SWV_{SOL} reflect the biarticular nature of MG; SWV_{MG} increases more when it is in a kinematic position that facilitates greater force generation.

The strong relationship observed between SWV and k_{joint} is noteworthy and clinically relevant. Weak relationships between SWV and k_{joint} have been observed when assessed passively, between subjects, and using the moment-angle relationship to estimate k_{joint} [2]. However, our data suggest that *changes* in SWV are reflected on the joint level when assessed using more sophisticated measures of k_{joint} and taking into account inter-individual differences. Thus, researchers and clinicians may be able to use SWV as a guidepost for understanding joint stiffness changes with muscle-level specificity.

Surprisingly, no relationship was observed between SWV and estimates of k_{muscle} ($R^2 = 0.10$; RMSE = 10537.9 N/mm). Model outputs were highly sensitive to moment arm and k_{tendon} parameters. Moreover, the k_{tendon} estimates measured experimentally were likely low, as just the MG subtendon was assessed; low k_{tendon} inflates k_{muscle}. This is evidenced by non-monotonic within-subject k_{muscle} estimates over increasing activations. Future investigations may wish to model each triceps surae muscle-subtendon unit, while considering the specific properties of each, as has been done in the upper extremity [8].

CONCLUSIONS

Our results indicate that changes in muscle SWV are indicative of changes in k_{joint} in healthy, young adults, and suggest that SW ultrasound elastography may be useful for assessing the etiology of changes in k_{joint} by providing muscle-level specificity.

REFERENCES

1. Kearney, et al., *Crit. Rev. Biomed. Eng.* **18**(**1**), 55-87, 1990.
2. Jakubowski, et al., *Clin. Biomech.* **49** 48-55, 2017.
3. Eby, et al., *J. Biomech.* **46**(**14**), 2381-7, 2013.
4. Ludvig, et al., *IEEE Trans. Biomed. Eng.* **59**(**12**), 3541-9, 2012.
5. Rouse, et al., *IEEE Trans. Biomed. Eng.* **60**(**2**), 562-8, 2013.
6. Arnold, et al., *Ann. Biomed. Eng.* **38**(**2**), 269-79, 2010.
7. Hashizume, et al., *J. Biomech.* **47**(**12**), 3226-31, 2014.
8. Hu, et al., *J. Neurophysiol.* **105**(**4**), 1633-41, 2011.

ACKNOWLEDGEMENTS

This study was funded by the ASB Graduate Student Grant-In-Aid. The authors would like to thank Dr. Daniel Ludvig for his technical assistance.

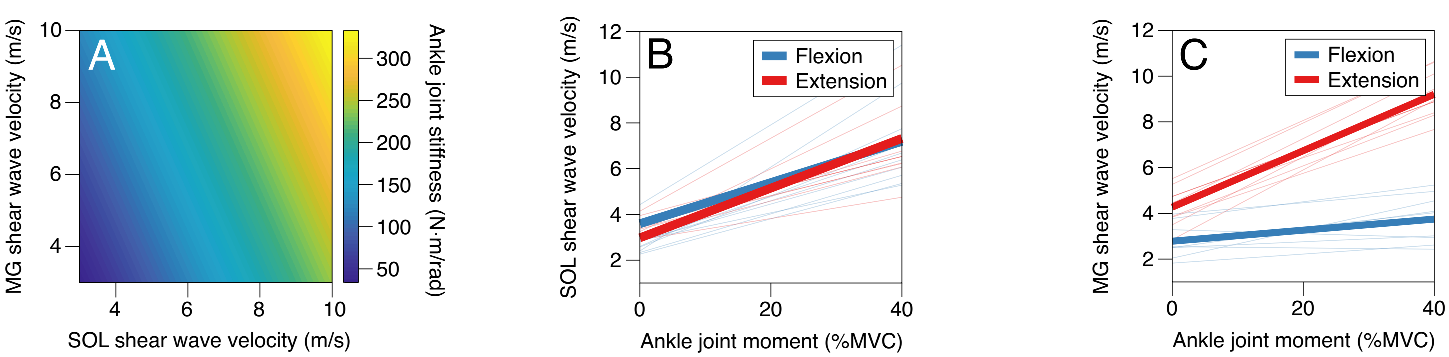

Figure 2: Relationships between shear wave velocity and joint-level measures. (A) Joint stiffness (color), soleus (SOL) shear wave velocity, and medial gastrocnemius (MG) shear wave velocity. Relative net joint moment and (B) SOL shear wave velocity and (C) MG shear wave velocity with the knee flexed (blue) and extended (red).