Non-uniform three-dimensional deformation of skeletal muscle during voluntary contraction *in vivo*

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Summary

Here we demonstrate non-uniform deformation of the vastus lateralis during submaximal voluntary contraction in human subjects. Through shape analysis, we show three-dimensional (3D) muscle deformation during isometric voluntary contraction, with outward bulging of anterior and posterior regions of the muscle while the central region shrank inward.

Introduction

Skeletal muscle shape greatly changes as it contracts to generate force. The dynamic muscle behavior during contraction is fundamental knowledge for understanding of muscle functionality. Muscle shortens and consequently expands transversely during contraction, which stems from two-dimensional evaluation. As contraction-induced change in muscle shape interacted with surrounding tissue [1], muscle does not necessarily deform outward, highlighting the comprehensive description of muscle deformation in 3D, yet this is not well explored. This study aimed to elucidate muscle deformation during voluntary contraction in human subjects by employing 3D shape analysis.

Methods

Anatomical images of the right thigh were obtained from nine healthy males (27 ± 4 yrs; 170 ± 5 cm; 69 ± 10 kg) using a 3 T magnetic resonance imaging (MRI) scanner with Dixon sequences during resting and contractile states. Each participant lay supine during the resting state whereas during the contractile state they performed isometric voluntary contraction by maintaining their leg at a target height that was priorly ensured to activate the vastus lateralis muscle to 20% of maximum voluntary contraction by electromyography. The boundary of the vastus lateralis was manually traced on the images (Fig. 1A), and the 3D surface shape model of vastus lateralis was constructed for both resting and contractile states (Fig. 1B). The muscle volume, cross-sectional area, length, width, and thickness were calculated and compared between resting and contractile states. For shape analysis, the surface distance of 3D shape model between resting and contractile states was computed and its difference was compared in anterior, central, and posterior regions of superficial side.

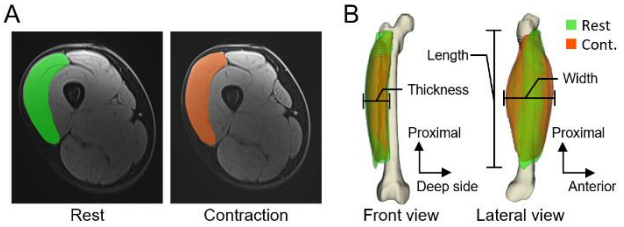

Figure 1: MRI (A) and 3D muscle shape of vastus lateralis (B) in resting and contractile states for a representative subject.

Results and Discussion

During contraction, muscle length shortened ($p < 0.001$) and width increased in middle and proximal regions, but thickness decreased in the middle region while total volume was preserved ($p = 0.561$). Although cross-sectional area did not change along with length, position of maximum cross-sectional area was displaced from proximal to middle regions ($p = 0.016$).

Shape analysis showed non-uniform deformation of vastus lateralis. Intriguingly, anterior and posterior muscle regions bulged outward while the central region shrank inward during contraction (Fig. 2A). Maximum bulge and shrinkage occurred in anterior (6.9 ± 2.1 mm) and central (−7.8 ± 2.9 mm) regions, respectively (Fig. 2B). In the comparison of average deformation (i.e., mean surface distance), the central region significantly shrank compared with anterior ($p < 0.001$) and posterior ($p < 0.001$) regions (Fig. 2C).

As muscle contracts, muscle fundamentally expands outward due to transverse force and fascicle rotation. However, counterintuitively, the vastus lateralis not only bulged but also shrank depending on the region during contraction. Because muscle contraction interacts with surrounding muscles and passive tissues [2], the bulging may be constrained by the iliotibial band passing lateral to the vastus lateralis, yielding non-uniform deformation. The 3D representation of skeletal muscle is needed to deepen our understating of how muscle deformation affects muscle contraction mechanics.

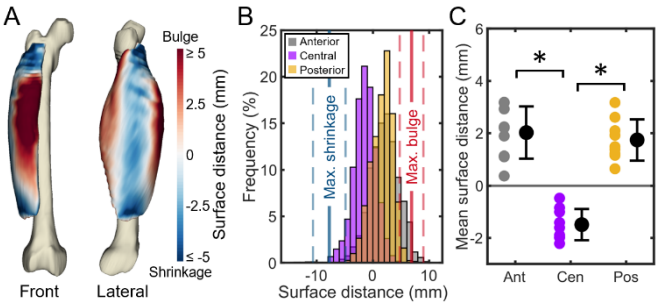

Figure 2: **(A)** Muscle deformation of a representative subject. **(B)** Bulge and shrinkage in anterior, central, and posterior regions. **(C)** Average deformation of each subject in three different regions.

Conclusions

3D shape analysis revealed simultaneous bulge and shrinkage during submaximal isometric voluntary contraction within human vastus lateralis muscle.

References

[1] Wakeling J et al. (2020) *Front Physiol*, **11**: 813.
[2] Finni T et al. (2008). *J Appl Physiol*, **104**: 1320-1328.