Non-Invasive Estimates of Skeletal Muscle Forces Using Ultra-Wideband (UWB) Radar

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Summary

Here, we demonstrate the novel use of ultra-wideband (UWB) radar as a tool to non-invasively estimate skeletal muscle forces, across different muscle architectures and contractile conditions. These include isometric contractions in the vastus lateralis (VL) (with and without fatigue) and tibialis anterior (TA), as well as dynamic contractions in the VL.

Introduction

Non-invasive estimates of muscle forces provide valuable insights in areas of biomechanics, sports science, and rehabilitation engineering. However, current methods can be limited in their accuracy, and have issues including muscle fatigue, co-activation, or low sampling rates. In this study, we use ultra-wideband (UWB) radar as a novel tool to non-invasively estimate muscle forces, by measuring changes in the electromagnetic properties of contracting skeletal muscle.

Methods

UWB data were collected using a LiteVNA (Vector Network Analyser) [1] and body matched antennas [2] over the muscle belly (10 Hz across 51 frequencies from 100 MHz - 2.9 GHz). Surface electromyography (sEMG) was used to measure muscle activation, and monitor fatigue and co-activation. B-mode ultrasound (US) was used to determine muscle fascicle length, velocity, and pennation. 20 participants (f=10; 22.6±3.4 yr) completed isometric knee extensions at 10, 20, 30, 40, and 50% MVC, and 20-min of contractions up to 45% MVC to induce fatigue. sEMG from VL and vastus medialis (VM), and UWB radar and US of VL were recorded. 6 participants (f=3; 24.7±1.8 yr) completed isometric ankle dorsiflexion contractions at 10, 20, 30, 40, and 50% MVC with biofeedback. sEMG, UWB radar and US of TA were recorded. 6 participants (f=3; 24.5±2.2 yr) completed dynamic knee extensions in an isokinetic dynamometer under passive, isokinetic, and isotonic conditions. sEMG of VL and VM, and UWB radar and US of VL were recorded.

Results and Discussion

We found a significant fixed effect of force on UWB radar for both the VL (Figure 1) and TA during isometric contractions (both $p<0.001$). For each participant, a long short-term memory machine learning model was trained on individual data to estimate muscle forces from the UWB radar scans of VL during fatiguing contractions. Each model was evaluated using 5-fold cross-validation (CV). Initial results from the first three participants provided an average test R^2 of 0.975 and RMSE of 2.0% MVC (6.1 Nm).

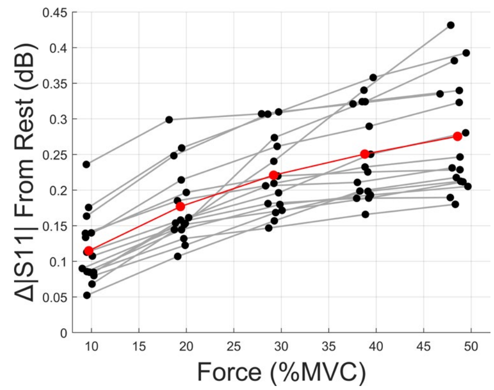

Figure 1: Change in VL UWB magnitude from rest to contracted, averaged across frequencies, from 10-50% MVC (n=16, $p<0.001$). Data is displayed for each participant (black) with mean (red).

During isometric contractions, factors such as muscle force, activation, and fascicle length remained well correlated with each other (all $R^2 > 0.8$). The purpose of the dynamic contractions was to decouple these parameters, and determine which factors contributed to the change in UWB radar signal. Preliminary results reveal that muscle force, activation, and fascicle length were successfully decoupled (all $R^2 < 0.2$), but each parameter had a significant fixed effect on the radar data (all $p<0.001$). Linear mixed effects models showed that different parts of the UWB radar data (magnitude/phase and reflected/transmitted, across the frequency range) were independently affected by different combinations of these parameters. These models were able to estimate dynamic changes in knee torque from the UWB radar data, with an average test R^2 of 0.971, and RMSE of 4.3% MVC (13.1 Nm). These models were evaluated with 5-fold CV.

Conclusions

Ultra-wideband (UWB) radar has been demonstrated as a promising technology for the non-invasive estimation of skeletal muscle properties. During isometric contractions of both VL and TA, muscle forces had a significant fixed effect on the radar scans. UWB radar was able to accurately predict VL isometric forces during fatiguing contractions with machine learning models. During dynamic contractions of VL, parameters including muscle force, activation, and fascicle length were all found to independently affect different parts of the UWB radar data, such that knee torque could be estimated using linear mixed effects models.

References

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