NON INVASIVE MONITORING OF IN-VIVO MUSCLE-TENDON MECHANICAL PROPERTIES OF ATHLETES WITH AN ULTRASONIC DETECTION SCHEME

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A system has been developed and applied for monitoring where the lateral muscle extension is detected with the aid of an ultrasonic caliper. Ultrasonic monitoring is furthermore used to detect synchronously the force exerted by the activated limbs. The resolution for muscle extension is ± 0.01mm and that of force is ± 1.5N. The force-length relation is observed for the gastrocnemius muscle for rising voluntary isometric contraction up to maximum contraction and subsequent relaxation. The measurement principle is based on synchronous monitoring of variations of the time-of-flight of the ultrasound passing the muscle and synchronous monitoring with an ultrasonic force sensor that also serves to keep the flexion of the joint constant. The observed force-length relation displays a hysteresis that is indicative of the athlete's training condition.

KEYWORDS: Monitoring of muscle force-length relation, hysteresis curve, bio-mechanical monitoring, non-invasive dynamic ultrasonic monitoring.

INTRODUCTION: For practical reasons, sudden changes in muscle length have commonly been used to assess the mechanical properties of the muscle. The force and lateral deformations recorded simultaneously from the same muscle can be used to determine the properties of the involved muscle fibers (Tarata, M. T., et. al. 2001). These studies were based on accelerometers placed on the observed muscle. The ultrasonic caliper employed here (Zakir Hossain, M., et.al., 2008 and 2009) is capable to directly determine the muscle extension with high spatial and temporal resolution, avoiding a double integration needed for accelerometers. The developed ultrasonic monitoring system is employed here to quantify a number of muscle performance parameters such as muscle force, recovery time, muscle endurance, muscle fatigue, work-done, contraction force, joint reaction force, speed of isometric muscle contraction and relaxation, steadiness of the holding phase, muscle length-diameter variation due to applied stress, hysteresis effect of a close-loop muscle actions, muscle stiffness, and the undershoot and overshoot due to isometric tetanus followed relaxation et cetera.

METHOD: Ultrasonic monitoring is performed on the lower leg of the person under study with the ultrasonic transducers placed for monitoring of the gastrocnemius muscle (figure 1). The force exerted by the muscle is monitored via the foot of the athlete with an ultrasonic force sensor that also keeps the joint angle constant. The monitored force relates to the torque produced by the gastrocnemius muscle. It is measured for rising isometric contraction and subsequent relaxation (figure-1). The ultrasonic monitoring scheme including the involved data processing has been published earlier (Zakir Hossain, M., et.al., 2008 and 2009). The monitored athlete is advised to push the foot down with maximum possible effort, hold as long as possible, and suddenly withdraw the pushing force. The position of the foot and joint angle is kept unchanged with a suitable arrangement. Evaluation of the collected data is performed by dedicated LabVIEW software. Conventional fitting is employed to quantify the performance variables of the monitored gastrocnemius muscle.

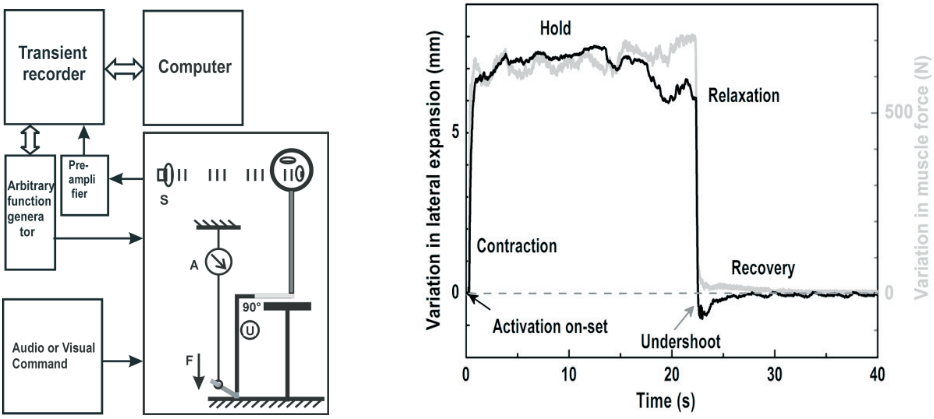

Figure 1: The schematic diagram at left shows the data acquisition set-up with: S: audio signal, U: ultrasonic monitoring, F: delivered force, and A: ultrasonic force sensor. The graphs at right depict the obtained data for muscle movement (black) and the exerted muscle force (gray).

RESULTS AND EVALUATION: The graphs displayed in figure 2 illustrate the monitored muscle force in relation to the monitored lateral muscle expansion for pre- and post-physical loading condition. The different phases of muscle action are indicated to exemplify the loading effect on muscle performance. It is observed that the muscle force increases and decreases in an irregular fashion with lateral elongation and diminution for pre- and post-physical loaded conditions. In the relation observed for pre- and post-loading, it is observed that the force increases rapidly till around 50% of deformation and decreases quicker again till around 50% of reformation phases.

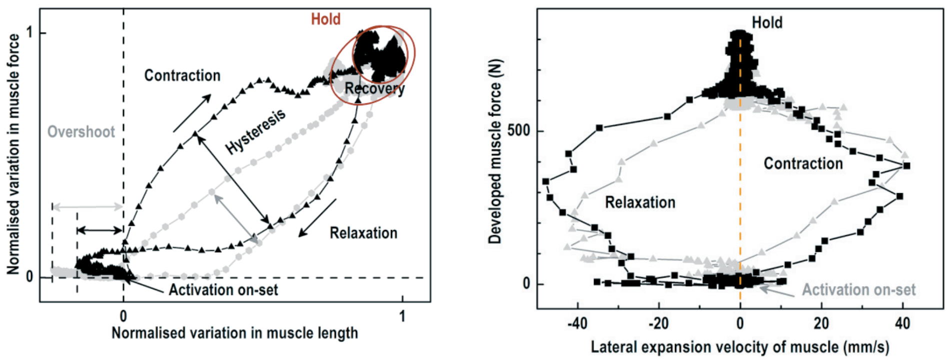

Figure 2: Variation of the applied muscle force-lateral expansion (left) and force-expansion velocity (right) values for pre (black) and post (gray) loading monitoring respectively. Amplitude values are normalized.

The hysteresis effect in post-loading is comparatively lesser than that of the pre-loaded muscle force-length loops. In both graphs it is also observed that during holding time the variation in force with respect to lateral expansion is larger in post loading muscle that the unloaded one (figure 2; area enclosed by ellipse). The under-shoot effect shows an increment for the loaded muscle too.
In figure 3 we have illustrated the monitored muscle's length-diameter variation due to the observed muscle action for prior (left) and post (right) physical loading condition.

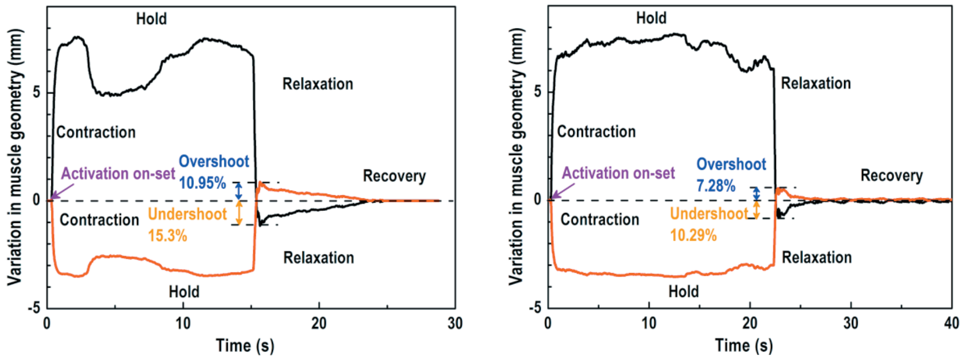

Figure 3: Variation of the muscle length verses lateral expansion and reformation for pre- (left) and post-loading (right) monitoring.

Pre-physical loaded muscle length variations range from 15 mm to 11.5 mm for the applied muscle force variation from zero to 700 N as determined via the foot. That is the length of the muscle belly varies between zero to 3.5 mm and the diameter varies between zero to 7.3 mm. Observed undershoot and overshoot are 1.69 mm and 1.34 mm respectively relating to 15.3% and 10.95% respectively. In post physical loaded muscle the variation of length is observed between 15 mm to 11 mm for the applied muscle force of 800 N. The maximum variation in diameter of the muscle belly observed for the post physical loaded monitoring is 8.47 mm and the length variation is determined to be 3.9 mm. The observed undershoot and overshoot are 1.56 mm and 1.24 mm respectively relating to 10.29% and 7.28% respectively to the maximum variation.

In figure 4 the variation in muscle length with respect to variation in developed muscle force are shown. The left graph illustrates the quantitative interpretation of a close-loop cycle "relaxation-MVIC-hold-relaxation" of the undisturbed gastrocnemius muscle activity.

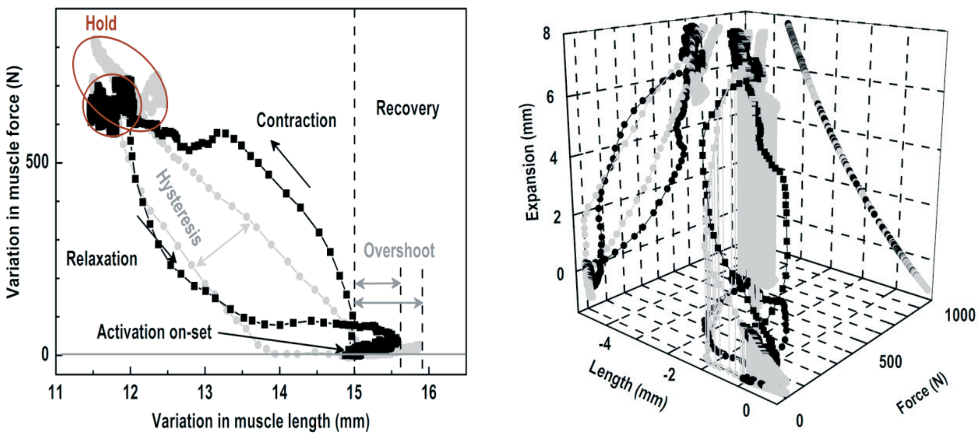

Figure 4: The left graph displays the muscle length-force variation for pre- (black) and post-physical loading (gray) monitoring. The right graphs represents the length-diameter-force variation for pre-loading and post-physical loading condition. The axes relate concerning "Expansion" to the monitored lateral muscle extension, concerning "Length" to the muscle length derived from the observed extension, and concerning "Force" to the measured force relating to the muscle force by a factor given by the geometry of the foot and lower limb.

The pre- and post-loading monitoring shows clear deviations in different phases. In the three dimensional representation, the variation of the lateral expansion, the respective variation of muscle length, and the observed force is displayed. It is observed that the muscle force-length, force-lateral deformations variations are almost identical but opposite in nature but the muscle length-lateral deformation with respect to applied force are almost linear. The shortening of the muscle at the muscle belly region is about 3 mm. This is compensated by the lengthening of the tendons on both end of the muscle belly that attach the gastrocnemius muscle to the bones. This lengthening happens because both ends are kept fixed under the given conditions while the muscle is contracted up to maximum possible effort by the monitored athlete.

The monitored maximum forces applied during pre- and post physical loading condition are 700 N and 800 N respectively. Under the experimental conditions the distance of the tendon from the ankle joint was one third (±10%) of the distance from that joint to the line where the force is monitored in vertical direction to the lever. Therefore the measured force has to be multiplied by 3 to get the actual force on the tendon connected to the gastrocnemius muscle.

The only other force that we have not used is the joint reaction force – the load on the joint that has no rotational component since it is acting at the fulcrum. Note that the signs of the forces relate to their direction. In this case our positive forces are acting downwards and our negative forces are acting upwards. Using the formula below:

(Force of gravity on sensor) + (Force of gravity on foot) + (muscle Force) + (Joint Reaction Force) = 0

That is 700 + 15 - 2100 + Joint Reaction Force = 0.

The Joint Reaction Force for pre-loading is 1385 N and for post loading is 1585 N.

DISCUSSION AND CONCLUSION: This study addresses a quantitative comparison between muscle length respectively diameter variation and force for the selected muscle. The results derived from the monitored behavior give detailed insight into the dynamics and show different results for physical loaded and non-loaded conditions. The detection scheme is non-invasive, easily accessible and cost effective. Quantitative findings ensure its applicability in on-line monitoring of so far unobserved parameters. These include muscle stiffness, muscle endurance, muscle fatigue, work-done due to isometric tetanus, contraction force, joint reaction force, speed of isometric muscle contraction and relaxation, steadiness of the holding phase, stress, and muscular endurance. The undershoot and overshoot due to isometric tetanus followed relaxation has been observed by this method for the first time. The trainers have the possibility to assess the effect of loading imparted on the athletes. Regular monitoring of this kind will help to design an effective training plan thereby ensures the maximum development of each individual performance variable separately and by this the athlete's performance as a whole.

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