MODEL OF CALF MUSCLE TEAR DURING A SIMULATED ECCENTRIC CONTRACTION.
A FEASIBILITY STUDY

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Tearing of muscle-tendon complex is one of the main causes of sport injuries. The aim of this study was to combine passive stretching and contraction to model the conditions of such injury, using the discrete element method. The mechanical behavior of the muscle-tendon complex was in agreement with data from the literature and data from in vitro experiments by tensile tests on calf muscle-tendon unit. The localization of the rupture and the pattern of rupture show a delamination of muscle’s fibers close to the myotendinous junction during an active stretching of the muscle-tendon complex.

KEY WORDS: muscle-tendon complex, fiber, contraction, rupture, injury.

INTRODUCTION: Tearing of a muscle-tendon complex (MTC) is one of the major causes of sport injuries. It occurs mainly during an eccentric contraction when muscle activation is combined with an extensive stretching (Uchiyama et al., 2011). This injury causes an alteration of the MTC’s mechanical properties (Uchiyama et al., 2011). However, while it could help treating and preventing such injury, neither involved structures nor mechanisms of rupture have been yet clearly identified (Pratt et al., 2012). Achilles tendon (AT) is one of the most frequently ruptured tendons but the mechanism of healing process and treatment is still under debate. A better understanding of the mechanisms leading to such injury could help clinicians to improve the way they manage the rehabilitation period of the athlete. The MTC is a multi-scale complex structure with non-isotropic and non-continuous mechanical properties. Many models use the Finite Element Method to simulate MTC’s behavior as a hyper-viscoelastic material (Gras et al., 2012). The Discrete Element Method (DEM) (Cundal and Starck, 1979) used for modeling composite materials seems to be adapted to fibrous materials as the MTC and to model the rupture, with simple mechanical laws.

The aim of this study was to model, with DEM, the MTC tear during a tensile test when muscle is pre-activated. This study has been done on calf muscle-tendon unit to be validated thanks to in vitro experiments (Roux et al., 2015).

METHODS: Firstly, MTC’s model was created with DEM. Secondly, tensile rupture test was validated. Then, muscle activation was validated. Finally, all previous parts were combined to model the muscle activation during a tensile rupture test.

1- MTC’s model design: The calf muscle-tendon unit was modeled with DEM (Figure 1-A). Muscle’s fibers were created by spherical discrete elements linked by springs. Each muscle of the calf muscle was implemented with a specific pennation angle (gastrocnemius muscles = 17° and soleus muscle = 23°, Chow et al., 2000). In order to simplify the model, we assume that those muscles insert on Achilles tendon at the same level. Similar method was applied to tendons’ fibers with finger-like insertion into the muscle to represent the myotendinous junction (MTJ) (Turrina et al., 2013). Extracellular matrix (ECM) was added into muscle by springs, between fibers, in all directions to model the anisotropy of the MTC.
Mechanical properties of each spring of the MTC components were addressed thanks to the literature (Table 1). The stiffness of the spring was linked to the Young's modulus of the MTC's component, its cross-sectional area and its initial length. However, no mechanical properties are available in the literature for ECM or MTJ: therefore, they were adapted from tendon and muscle mechanical properties. ECM's mechanical properties were adjusted to fit in vitro experimental data from Gras et al. (2012) on the sternocleidomastoid muscle (Roux et al., 2016).

Table 1: Young's modulus of muscle-tendon complex's components (adapted from Roux et al., 2016)

<table>
<thead>
<tr>
<th>MTC's Components</th>
<th>Young's Modulus (MPa)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendon's Fiber / Epimysium</td>
<td>860</td>
<td>Matsuziko et al., 2013</td>
</tr>
<tr>
<td>Muscle's Fiber</td>
<td>0.0744</td>
<td>Roux et al., 2011</td>
</tr>
<tr>
<td>Myotendinous Junction</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>ExtraCellular Matrix</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

2- Tensile test until rupture (ISB 2015 (Roux)). The GranOO software (www.granoo.org) was used to model the MTC and to simulate the tensile test until rupture. The upper base of the MTC was fixed. On the upper base of the MTC, a linear displacement was applied in quasi-static conditions (1 mm/s). The force/displacement curve was similar to experimental ones (Gras et al., 2012). The non-linear hyper-elastic properties of the MTC were highlighted (Figure 1-B). The passive rupture of the MTC was caused by delamination of fibers, close to the MTJ (Roux et al., 2015).

3- Tests of muscle activation on the MTC: A preliminary study was done on muscle's fibers with a simplified parabolic force/length relationship. A force is added into the mechanical behavior of the spring constituting the fiber, to model the active behavior of the fiber:

\[
\begin{align*}
F &= F_{max} \alpha \left(1 - \left(\frac{\Delta l}{l_c}\right)^2\right) \quad \text{if} \quad l_c \geq |\Delta l| \geq -l_c \\
F &= 0 \quad \text{else}
\end{align*}
\]

Each point of the force/length relationship was obtained with two steps: 1) a passive tensile (or contraction) test until the desired elongation and 2) fiber isometric activation during a static position held by the fiber. To avoid vibrations and numerical problems, fiber was slowly activated. Activation of all MTC's fibers previously built was applied. In this feasibility study, the same active behavior was applied on muscle's fibers of the MTC. The force/length relationship of the MTC was studied with the specific sequence of mechanic test following by muscle activation during a static position held by the MTC. The lower base was fixed while the linear displacement was applied on the upper base during the first phase. The order of magnitude was also studied and compared to the theoretical value given by (Winters et al., 1988): \( F_{c, max} = \sigma_{max} \times \text{PCSA} \) with \( F_{c, max} \): maximal isometric force, PCSA: Physical Cross-Sectional Area and \( \sigma_{max} = 0.5 \text{ MPa} \): maximal isometric stress. For a fiber, the force/length relationship was agreed with literature (Woitiez et al., 1983) (Figure 1-C).
4- Tests of muscle activation during a tensile test until rupture: The aim of this study was to combine muscle activation with a tensile test until rupture (1 mm/s - quasi-static test), to fix conditions observed for MTC's tear. The lower part of the MTC was fixed and a linear displacement was applied on the upper part. During the tensile test, muscle activation will be also applied with results previously found. For this feasibility study, the same force/length relationship was simultaneously applied to all muscle's fibers.

5- Data analysis: The force/displacement curve was studied during the whole simulation with numerical visualization. The localization of rupture, its mechanisms and involved structures were analyzed, as well as stress inside each discrete element to detect stress concentration area.

RESULTS AND DISCUSSION: The non-linear hyper-elastic behavior of the MTC is confirmed and in agreement with the literature (Gras et al., 2012) (Figure 2-A). The active behavior of the MTC is similar to behaviors reported by Woitiez et al. (1983). The parabolic relationship was an adapted model to validate the active behavior of fibers. The end of the active behavior was not exactly at the length $l_0$ because of the viscous behavior of components inside the muscle (ECM). During the activation of all the fibers, the mechanical behavior of the MTC was validated ($F_{c,max, \text{num}} = 49.8 \text{ N vs. } F_{c,max, \text{Winters}} = 48.2 \text{ N and similar aspect of the force/length relationship}$).

The speeds of the model and experiments are lower than dynamic rate studies in literature (Pratt et al., 2012) because it initially overcomes the inertial effect during the simulation. Ongoing work with high speed simulations will allow to fit with experimental data on the tear of the muscle and to reproduce clinical conditions for this injury. The approximation of the geometrical shape of the MTC gives good results. Its mechanical properties were obtained and adjusted with mean values from the literature. An improvement of mechanical properties, more specific to the MTC studied could be done (i.e. mechanical tests or shear wave elastography).

Figure 2: A. Representation of the force/displacement curve of the MTC during an active tensile test until rupture. Fiber's delamination is located at the level of black arrows. B. Rupture of the MTC during an active tensile test with an expanded view of the myotendinous junction

Delamination of muscle's fibers was observed close to the MTJ (Figure 2-B). This pattern of rupture is in agreement with literature (Pratt et al., 2012). The stress concentration, close to the MTJ, reveals that this region will be subjected to important forces and therefore ruptures. One reason could be the difference of mechanical properties between the muscle (soft) and the tendon (stiff). Numerical results are also in agreement with literature (80% of rupture in the MTJ's site, Illaslan et al., 2007) and with in vitro tests on calf muscle-tendon unit where rupture occurred in 13 over 14 cases at the JMT's level and only one with tendon avulsion (Roux et al., 2015). A first high delamination is observed and then a second rupture highlights the global delamination of the MTJ with a wrenching of muscle's fibers (black arrows on Figure 2-A). Validation of the model will be done with experimental data on calf muscle-tendon unit from human cadavers in passive quasi-static tests. An extended study should be done with fresh cadavers. However, because of the complexity of this kind of experiments, validation of each behavior (active and passive) was preferred.
CONCLUSION: The DEM is a promising method for modeling the tear of the MTC. The shape of numerical curve was in agreement with the ones obtained experimentally, confirming the possibility of modeling the non-linear, hyper-elastic macroscopic response of a muscle with simple, linear, elastic, microscopic elements. The muscle activation was implemented into a spring model, thanks to a force/length law for the muscle’s fibers, to model an eccentric contraction. This feasibility study shows the possibility to model the tear of the MTC by muscle activation during a tensile test. To improve the model, an increase of the speed solicitation and an improvement of mechanical properties and geometrical shape of the MTC could be done. The long term objective of this study is to prevent injury by predicting, with appropriate model, the tear or not of the MTC, having access to MTC in vivo mechanical properties.

REFERENCES:


