MODEL OF CALF MUSCLE TEAR DURING A SIMULATED ECCENTRIC CONTRACTION. A FEASABILITY 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 = 25°, 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.

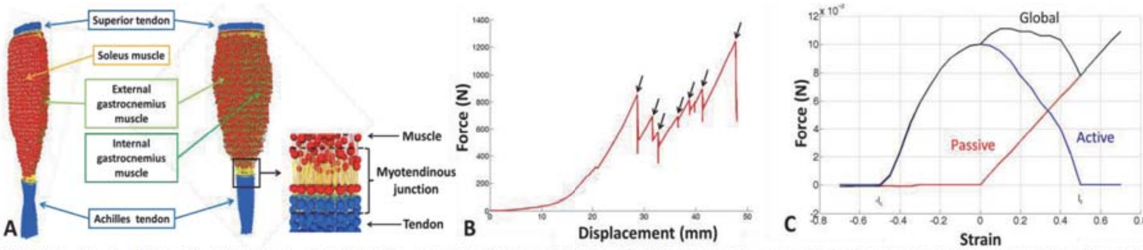

Figure 1: A. Muscle-tendon complex's geometry with the DEM with an expanded view of the myotendinous junction. B. Representation of the force/displacement curve of the MTC during a passive tensile test until rupture. Fiber's delamination is located at the level of black arrows. C. Representation of the force/length relationship of a muscle's fiber with its passive, active and global mechanical behaviors.

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 sternocleidomastodeus muscle (Roux *et al*., 2016).

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

MTC's Components	Young's Modulus (MPa)	Reference
Tendon's Fiber / Epimysium	800	Matschke et al., 2013
Muscle's Fiber	0.03744	Regev et al., 2011
Myotendinous Junction	400	-
ExtraCellular Matrix	0.1	-

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:

$$\begin{cases} F = F_{max}.\alpha.\left(1-\left(\frac{\Delta l}{l_c}\right)^2\right) & if \quad l_c \geq |\Delta l| \geq -l_c \\ F = 0 & else \end{cases}$$

F_{max}: maximal isometric force
α: percentage of muscle activation coefficient
Δl: elongation of the muscle's fiber
l_c: characteristic activation length
(end of contraction effects, $l_c = 0.56 \times l_0$)(Woitiez *et al.*, 1983)
l_0: initial length of the fiber

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): $F_{c,max} = \sigma_{max}.PCSA$ with $F_{c,max}$: maximal isometric force, PCSA: Physical Cross-Sectional Area and σ_{max} = 0.5 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_c 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 ($F_{c,max,num}$ = 49.8 N vs. $F_{c,max,Winters}$ = 48.2 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).

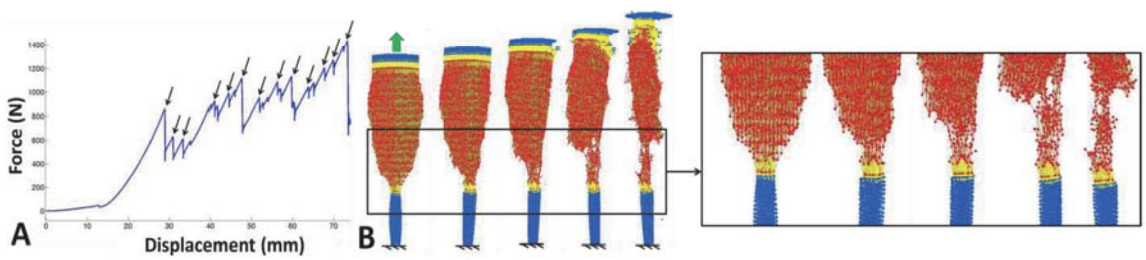

Figure 2: A. Representation of the force/displacement curve of the MTC during an active tensile test until rupture. Fiber's delamination is located at the level of black arrows. B. Rupture of the MTC during an active tensile test with an expanded view of the myotendinous junction

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, Ilaslan *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:

Chow, R. S., Medri, M. K., Martin, D. C., Leekam, R. N., Agur, A. M., & McKee, N. H. (2000). Sonographic studies of human soleus and gastrocnemius muscle architecture: gender variability. *European Journal of Applied Physiology*, 82(3), 236-244.

Cundall, P., & Starck, O. D. L. (1979). A discrete numerical model for granular assemblies. *Géotechnique*, 29, 47-65.

Gras, L.-L., Mitton, D., Viot, P., & Laporte, S. (2012). Hyper-elastic properties of the human sternocleidomastoideus muscle in tension. *Journal of the Mechanical Behavior of Biomedical Materials*, 15, 131-140.

Ilaslan, H., Iannotti, J. P., & Recht, M. P. (2007). Deltoid muscle and tendon tears in patients with chronic rotator cuff tears. *Skeletal Radiology*, 36(6), 503-507.

Matschke, V., Jones, J. G., Lemmey, A. B., Maddison, P. J., Thom, J. M. (2013). Patellar tendon properties and lower limb function in rheumatoid arthritis and ankylosing spondylitis versus healthy controls: a cross-sectional study. *The Scientific World Journal*, 514743.

Pratt, S. J., Lawlor, M. W., Shah, S. B., & Lovering, R. M. (2012). An in vivo rodent model of contraction-induced injury in the quadriceps muscle. *Injury*, 43(6), 788-793.

Regev, G. J., Kim, C. W., Tomiya, A., Lee, Y. P., Ghofrani, H., Garfin, S. R., Lieber, R. L., Ward, S. R. (2011). Psoas muscle architectural design, in vivo sarcomere length range, and passive tensile properties support its role as a lumbar spine stabilizer. *Spine (Phila Pa 1976)*, 36, E1666--E1674.

Roux, A., Haen, T-X., Lecompte, J., Iordanoff, I., Laporte, S. (2015). Rupture of the Muscle-Tendon Complex in tensile test. Comparison between experimentations and discrete element modelling. *Computer Methods in Biomechanics and Biomedical Engineering*, 18, sup1, 2015.

Roux, A., Laporte, S., Lecompte, J., Gras, L.-L., & Iordanoff, I. (2016). Influence of muscle-tendon complex geometrical parameters on modeling passive stretch behavior with the Discrete Element Method. *Journal of Biomechanics*, 49, pp. 252-258.

Turrina, A., Martínez-González, M. A., & Stecco, C. (2013). The muscular force transmission system: role of the intramuscular connective tissue*. Journal of Bodywork and Movement Therapies*, 17(1), 95-102.

Uchiyama, Y., Miyazaki, S., Tamaki, T., Shimpuku, E., Handa, A., Omi, H., et al. (2011). Clinical results of a surgical technique using endobuttons for complete tendon tear of pectoralis major muscle: report of five cases. *Sports medicine, arthroscopy, rehabilitation, therapy & technology*, 3, 20.

Winters, J. M., & Stark, L. (1988). Estimated mechanical properties of synergistic muscles involved in movements of a variety of human joints. *Journal of Biomechanics*, 21(12), 1027-1041.

Woittiez, R. D., Huijing, P. A., & Rozendal, R. H. (1983). Influence of muscle architecture on the length-force diagram of mammalian muscle. *Pflugers Archiv*, 399(4), 275-279.