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Fascia Science and Clinical Applications

Sensory regulation and mechanical effects of sustained high intensity stretching of the anterior compartment of the thigh

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ABSTRACT

Background: Ballet dancers, contortionists, gymnasts, or other sportspeople spend long hours performing stretches while training. Although most studies on stretching consider fascia lengthening to be difficult, athletes manage to lengthen their fascia.

Aim: To assess the relationship between lengthening fascial structures of the anterior compartment of the thigh and the self-reported sensation of discomfort and pain during a sustained and repeated high intensity stretch.

Methods: Our analysis was based on the data of 7 high school male elite rugby players who completed 11 sessions of stretching (10-min quasi-static stretch of the rectus femoris and fascia lata, at the maximum intensity tolerated), performed twice per week. The measured outcomes included hip range of motion, the length of the structures of the anterior compartment, subjective pain and tension during the stretch, and the level of surface electromyography activity. Values were compared before and after completion of the 11 sessions.

Results: Myofascial length increased by 1 cm. The necessary force applied increased from 124 to 164 N. However, the maximal tolerated stretching intensity did not change significantly (from 205 to 206 N). The increase in length was principally contributed by the rate of fascial creep upon force application, and not by contractile tissue. Subjective levels of tension were related to the stretching force applied and pain was related to the lengthening.

Conclusion: Sensations can be used to adjust the intensity and duration of stretching. Soft matter physics provides a new interpretation of fascia lengthening and strengthening during a high intensity stretch.

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1. Introduction

There is an ongoing debate, with contradictory evidence, regarding the effectiveness of stretching to lengthen the fascial structures (Medeiros and Lima, 2017; Freitas et al., 2018; McHugh and Cosgrave, 2010; Thacker et al., 2004; Weppler and Magnusson, 2010; Marshall et al., 2011; Björklund et al., 2001). The fascia comprises a network of collagen fibres that can both store and transmit energy, as the structure shortens and lengthens, respectively (Zatsiorsky and Prilutsky, 2012; Schleip et al., 2012). Accordingly, lengthening the fascial structure increases its force

output by improving the transmission of mechanical strain within the muscle and from the muscle to its tendinous attachment on the bone (Medeiros and Lima, 2017; Freitas et al., 2018; Weppler and Magnusson, 2010).

The aim of stretching is to increase the length of both the muscle and its fascial components. However, it is well-known that increasing the length of a muscle through stretching alone is difficult (Medeiros and Lima, 2017; Freitas et al., 2018; Harvey et al., 2017). An external device may be required to generate the amount of force that is necessary to stimulate sarcomerogenesis (Zöllner et al., 2012; Caiozzo et al., 2002). A 10-min continuous high intensity stretch has been shown to be an effective stimulus for muscle lengthening (Rosario and Foletto, 2015; Germain and Regis, 2016). The response of a muscle to tolerable stretching stimuli is low (Freitas et al., 2018) and the increase in length with stretching exercises is difficult to detect.

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Most clinicians and trainers agree that lengthening the fascia improves flexibility and range of motion, and might also be useful in reducing the frequency of muscle injuries (McHugh and Cosgrave, 2010; Thacker et al., 2004). The intensity of the stretching stimulus would be regulated by feedback from mechanical, pain, and stretch receptors (Mow and Huijskes, 2005; Purslow, 2002). The interplay between the perception of stretching and the intensity of stretch is not currently well defined. In this regard, structural models of connective tissue (Purslow, 2002; Puxkandl et al., 2002) could be useful in understanding this dynamic interplay that has been suggested by some authors (Germain and Regis, 2016; Zatsiorsky and Prilutsky, 2012; Mow and Huijskes, 2005). Practically, the relationship between self-reported intensity of stretching and the effectiveness of a stretch can be evaluated by combining the subjective measurement of pain or discomfort perception with an objective measurement of increase in length of the fascial structure (and an increase in the range of motion of its associated joints).

Ultrasound-based technologies offer a quantitative method for measuring the length of the fascial tissue (Peixinho et al., 2014; Nakamura et al., 2014; Hirata et al., 2017; Abellana et al., 2006) and could be useful to differentiate the relative effectiveness of a stretch on the fascial structure. Specifically, shear-wave elastography has recently been used to quantify the tension of the fascial network within the *medial gastrocnemius* (Nakamura et al., 2014; Hirata et al., 2017). Although ultrasound-based techniques are useful to detect modifications in the architecture of the myofascial tissue with lengthening, these techniques are inaccurate to assess lengthening of tissues at speeds $<0.25\%/min$, recorded *in vivo*, during the lengthening process (Germain and Regis, 2016).

The clinical implication of determining the intensity of a stretch, without relying on quantitative measures, such as elastography, is the plausible relationship between the intensity of the stretch and the self-reported sensation caused by stretching. The regulation of this subjective perception allows the application of a higher intensity force (Thacker et al., 2004; Weppeler and Magnusson, 2010; Björklund et al., 2001). Even though surface electromyography presents many limitations (Byrne et al., 2005) it has been helpful in demonstrating increase in tension in the absence of changes in muscle activity (Magnusson et al., 1996), confirming that the change in physical characteristics of the structure primarily occurs in the fascia. Long duration static stretching can, however, reduce the contractile ability of the muscle (Lin et al., 2008). With the knowledge that the self-reported sensations produced by stretching is associated, to some degree, with the lengthening of the fascia during stretching, subjective feedback could be used by physiotherapists and other clinicians and trainers to regulate the intensity and duration of stretching to facilitate lengthening (Medeiros and Lima, 2017; Freitas et al., 2018; McHugh and Cosgrave, 2010; Weppeler and Magnusson, 2010; Germain and Regis, 2016; Harvey et al., 2017). Even though stress relaxation and creep phenomenon are well described (Zatsiorsky and Prilutsky, 2012; Mow and Huijskes, 2005; Gras, 2011; Gras et al., 2013), the relationship between physical aspects of lengthening and the sensation of tension and perceived discomfort reported by patients to clinicians (Weppeler and Magnusson, 2010) is not well established. For manual therapists, it is crucial to know what the patients feel when they lengthen a fascia during the treatment of all the diseases which involve fascial stiffness.

Accordingly, the aim of our study was to assess the relationship between fascial lengthening and stretch sensation after a stretching training consisting of 11 sessions of 10-min passive stretch in elite athletes. As long experiments are known to trigger creep responses *in vitro*, we hypothesized that lengthening the tissue would trigger the creep responses *in vivo*. The aim was to see the creep response

in vivo. We further hypothesized that the magnitude of the change in length would influence the biomechanical response of the structure to stretch by modifying its resistance to stretch. In fascial tissues, this biomechanical response is mediated by the viscoelastic compounds in response to the magnitude and velocity of lengthening. The secondary objective of this study was to examine the force, length, and muscle activity in order to confirm the preferential locus of the effect of the stretch at the level of fascia and/or the muscle contractile unit.

2. Methods

2.1. Statement of ethics

Our study design was approved by our institutional ethics review board and all participants provided informed consent.

2.2. Design

This longitudinal study was designed to observe physical changes induced by intense stretching. The follow up included biomechanical parameters such as fascial length and reaction force of the fascia. The subjective perceptions of tension and discomfort were also reported during each stretching session.

2.3. Study group

The study group consisted of 9 elite high school rugby players, because all their training sessions were supervised by their coach, with a mean age of 17, standard deviation (SD) = 0.5 years, an average height of 178, SD = 4 cm, and mean weight of 88, SD = 8 kg. We assessed both thighs. All participants completed 9 h of rugby-specific training per week, which included sprint training (using long strides as in match play) and playing matches on weekends. Their regular training program also included 3 h of strength training per week. However, the stretching component of the program included whole-body stretches, with a <30 s hold for each large muscle group, performed for <10 min per week. Of the 9 participants enrolled at the start of the study, 2 could not complete the 11 sessions due to injuries sustained during matches. As we intended to recruit a small group with homogeneous characteristics, we did not replace the dropouts. Considering our clinical experience, we noticed that the fascia of young healthy sportsmen was more easy to lengthen. As we wanted to show the kinetic of fascia lengthening during the experiment we chose a small group with healthy fascia. Moreover, we used a pre-post assessment design, with no control group as it is well established that the fascia is never lengthened without any intervention (Medeiros and Lima, 2017; Freitas et al., 2018).

2.4. Stretching intervention

A 10-min static stretch, applied at the highest tolerated intensity, was used as the stimulus of stretch, with a total of 11 sessions completed over a period of 6 weeks, performed twice a week. Each participant stretched both thighs. Stretching was applied to the anterior compartment of the thigh, as shown in Fig. 1. As per previously described methods, we used a passive stretching apparatus that stabilized the pelvis, such that the stretching force was specifically applied to the targeted muscle compartment (Umehara et al., 2015; Jensen and Davy, 1975; Otsuka et al., 2018), which includes the *rectus femoris* and *fascia lata*. The change in length of these muscles was measured by the change in range of motion of the hip in degrees during extension while knee flexion was fixed at 105° and the position of the pelvis was stabilized. This

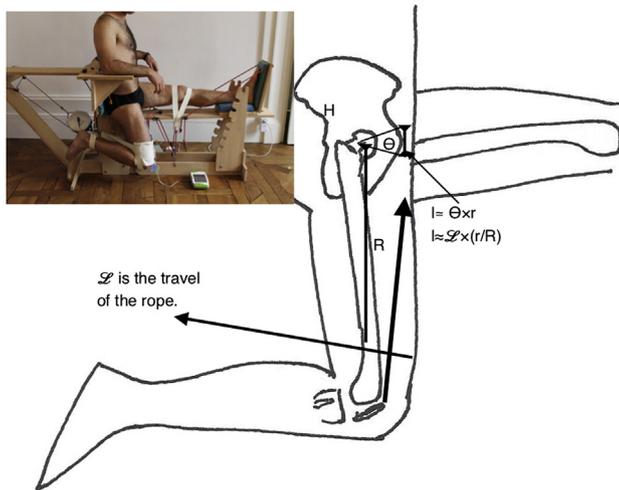


Fig. 1. The pulley system stretches the myofascial structures of the anterior compartment of the thigh.

The position of the pelvis was stabilized, using very high density pads. With this stabilisation, and the knee placed in a consistent angle of flexion, the vector force applied to the hip (H) can be calculated. Moment equations and the tendon travel method are used to calculate the tension applied to the compartment and the change in length.

L is the distance travelled by the rope, with each turn causing a 7 mm shortening of the rope. The tension in the rope can be calculated (N).

The tendon travel method is used to calculate the change in length, as follows: $l = \Theta \times r$, where Θ is the angle of change in the position of the femur (rad) and r is the radius of the circle, which provides the distance between the *fascia lata* and the centre of rotation of the hip (H). The relationship between ' l ' and ' L ' can be defined, as follows: $l \approx L \times (r/R)$. Accordingly, the change in length is measured from the length of the rope ' L ', which facilitates calculation of the length-tension graph. Note that there is a direct relationship between the angle Θ and the length ' l ' of the *fascia lata*.

method provided repeatable measures of pre-to post-intervention changes (Germain and Regis, 2016). During this stretching protocol, surface electromyography of the *rectus femoris* and *tensor fascia lata* did not show values above the 3 μV threshold of resting activity using our apparatus.

Before each session, the participants completed a warm-up, consisting of a 2-km slow walk on a treadmill. The stretch was applied 30° medial to the centre of the thigh to counteract the abduction moment of the *fascia lata*. The intensity of the stretch ranged between 30 and 130 N m, depending on each participant's tolerance. No feedback of the intensity of stretch was provided to the participants. The magnitude of the applied stretching force was increased at 2-min intervals, by the assessor, until the highest tolerated intensity was attained. Every 2 min, the assessor increased the tension until the participant said 'stop'. This meant that the assessor offered six tension increases during the sessions. The subjective rating of pain or discomfort was measured on a 10-point scale, from '1' (no discomfort) to '10' (maximal discomfort). We asked the participants to 'stop' the stretch each time the maximal bearable tension was reached and to grade pain/discomfort once this maximal tension was reached every 2 min. The outcomes were measured at baseline, prior to the first session, and at the end of session 11.

Therefore, in each trial, the intensity of stretch was determined by the participant, which allowed us to assess the relationship between the self-reported sensation of tension during the stretch and the magnitude of the force applied.

2.5. Measured outcomes

The velocity of the stretch was measured in $\text{mm} \cdot \text{min}^{-1}$, with

one turn of the rope and pulley system used to apply the stretch corresponding to a 1-mm increase in length of the structures of the anterior compartment of the thigh. For the *fascia lata* that has the longest fascia/tendon in the body (approximately 40 cm), a 1-mm increase in length would translate to a 0.25% increase in length specifically for that fascia. Based on the biomechanical literature, an increase in length would trigger the creep response of the fascial structure in response to an applied force during a 10-min stretch (Zatsiorsky and Prilutsky, 2012; Mow and Huijskes 2005; Gras 2011; Germain and Regis, 2016). Passive force applied by the pulley system was measured using a dynamometer, extending the hip and knee maintained in the same angular position for all trials (confirmed by taking pictures at every trial). As previously mentioned, discomfort/pain was assessed using a 10-point scale, using self-reported measurements obtained at 2-min intervals.

2.6. Data analysis

Changes in the measured outcome after session 11, from baseline, were evaluated using the Mann-Whitney U test, which is appropriate for a small sample. Fourteen thighs could be included after assessing the role of deviations and normal distribution of the results. The principal component analysis (PCA) was used to evaluate the association between the physical measures (applied force and range of motion) and the subjective sensation of stretching using the average data across the 7 participants who completed all 11 sessions. The change in force (or tension) per unit of time ($dT \cdot dt^{-1}$) was used to evaluate the recruitment of passive fibres. The tension-length graphs were used to assess the transition from lengthening due to fascial creep versus that due to the elastic components. All analyses were performed using STAT lab™ software. Soft matter physics theories De Gennes (1971), 1975; Puxkandl model (Puxkandl et al., 2002), and Maxwell body were used to examine the physical aspects of fascia lengthening.

3. Results

The range of hip extension increased over the 11 sessions ($p = 0.042$) and was associated with an average increase of 7.5 mm in length of the fascial structures of the anterior compartment of the thigh (at the same magnitude of the applied force). At the point of maximum tolerable intensity, the average increase in length was 10 mm ($p = 0.0016$). At the beginning of the stretch, the maximum tolerable intensity increased by 33%, on average, from baseline but did not change significantly at the end of the stretch. (Fig. 2, C-D). The tension increase at the beginning of the stretch was statistically obvious between stretch 1 and 11 ($p = 0.0061$) but we could not show any tension increase at the end of the stretch between stretch 1 and 11 ($p = 0.50$).

The degree of pain/discomfort perception did not change over the 11 sessions of stretching, with no indication of adaptation (Fig. 2G–H). The PCA (Fig. 3) indicates that the subjective sensation of pain during a stretch is related to the lengthening of the fascia, with no contribution from the rate of tension. Moreover, the subjective sensation of tension did not increase as a function of an increase in the length of the fascia.

The total bearable tension did not change between stretch 1 and 11 (205 N and 206 N, respectively), but $dT \cdot dt^{-1}$ (Fig. 4) indicated that recruitment of the collagen fibres occurred twice faster after 11 stretches. The magnitude of change in the lengthening response over the 10-min period of stretching was 18% lower during session 11 than that during session 1 (Fig. 2, A-B).

Using soft matter physics theories to analyse the results, we noticed that the fascia reacts as a Maxwell body. A Maxwell body can be represented by a purely viscous damper and a purely elastic

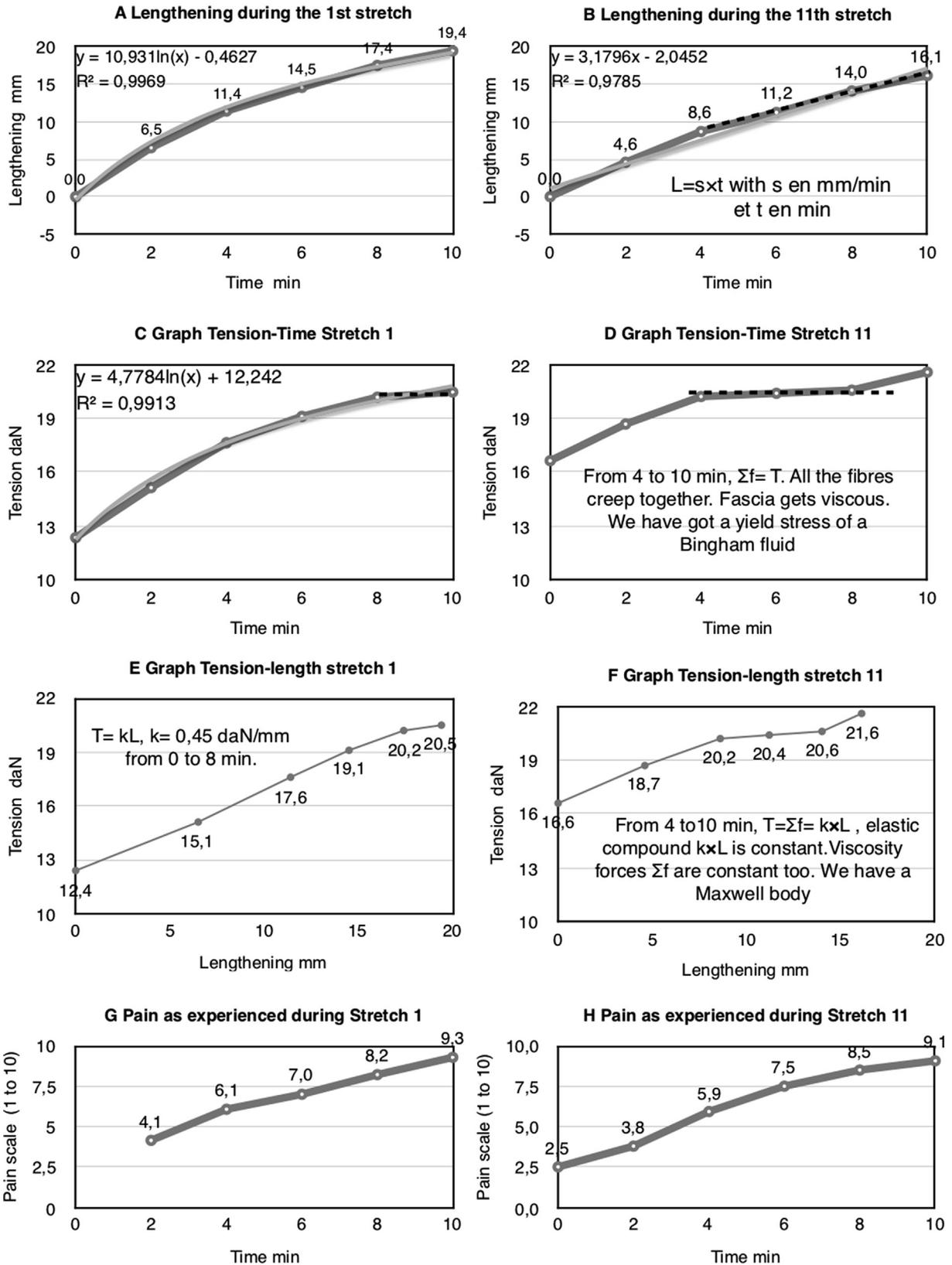


Fig. 2. Measured outcomes.

A–B: The change in length is smaller during stretch 11 than stretch 1. However, note that point ‘0’ (starting length) is at +7.5 mm (compared to baseline), which represents an absolute change in the length of the myofascial structures over the 11 weeks of the stretching program.

C–D: During stretch 11, the tension reaches a plateau, with lengthening occurring without recruitment of tensile elements. The creep response is observable in the time frame from 4 to 10 min.

E–F: During stretch 1, the tension-to-length ratio follows the law of elastics, but with a yield at the end-point of the stretch (20.2 daN). At this point, the myofascial structures cannot bear additional tension and, thus, the process of lengthening becomes viscous, with fascial creep not adding to the tension.

G–H: The subjective rating of discomfort and pain during stretching shows no change between stretch 1 and 11, being experienced at the same point in time during the stretch for stretch 1 and 11, pain is associated with creep and lengthening.

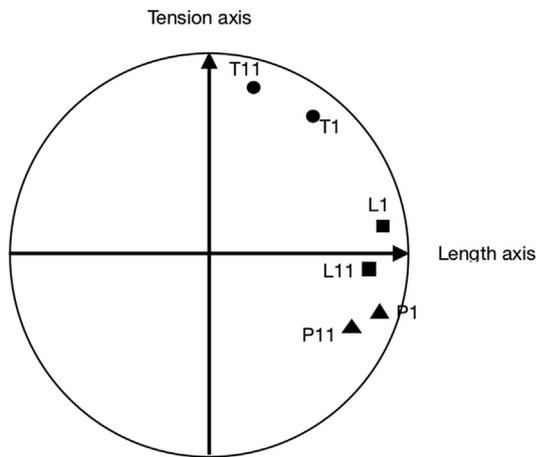


Fig. 3. Principal component analysis, showing the change in measured variables from stretch 1 to stretch 11. There is an apparent correlation between pain at stretch 1 and 11 (P1 and P11, respectively) and length (L1 and L11, respectively), and an apparent correlation between tension (T1 and T11, respectively) and the mechanical force applied. During stretch 11, P11 is dissociated from T11.

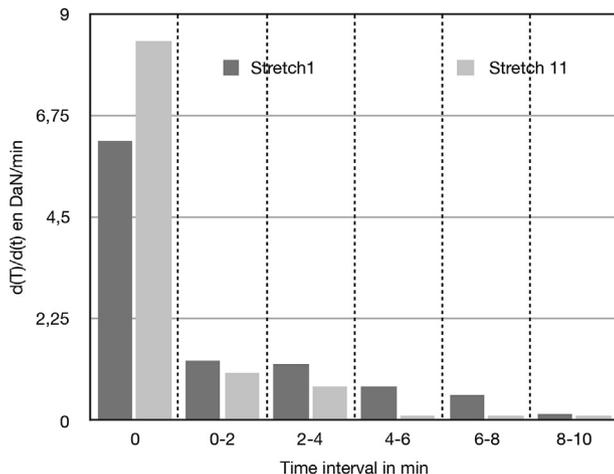


Fig. 4. The derivative $d(T)/dt-1$ shows the speed of recruitment of the fascial component. During stretch 1, all fascial (passive) fibres are recruited for 10 min. During stretch 11, this recruitment is completed in 4 min, indicative of a homogenized response of the fascia to the applied tension.

spring connected in series. Maxwell bodies are used to model stress relaxation of living tissues. The viscous compound would be a physical gel. The gel reached the yield stress after 4 min of stretching once the tissue reacted homogeneously (see $dT \cdot dt-1$ of the 11th stretch). This explained the constant lengthening speed from 4 to 10 min (Fig. 2 B). A simple model would be a spring anchored in a star-like polymer gel (Fig. 5).

4. Discussion

4.1. Effects of stretching on lengthening

A tolerable lengthening of 1 mm was achieved, on an average, per stretching session; this rate was greater than the previously reported values (Medeiros and Lima, 2017; Freitas et al., 2018; Björklund et al., 2001; Harvey et al., 2017). On an average, we applied 23 J of work during each stretching session. The effort of stretching is typically not reported as a component of the stretching programs (Medeiros and Lima, 2017; Freitas et al., 2018; Thacker

et al., 2004; Weppler and Magnusson, 2010; Umehara et al., 2015; Rosario and Foletto, 2015; Marshall et al., 2011; Björklund et al., 2001; Germain and Regis, 2016; Schleip et al., 2012). As confirmation of the validity of our protocol, the response measured was indicative of the effect of stretching on the fascia rather than the contractile components, and agreed with the data for tendon, measured *in vitro* during an applied stretch (Zatsiorsky and Prilutsky, 2012; Mow and Huijskes, 2005). Therefore, we suggest that the measured change in length was contributed by repeated creep responses of the fascia.

The model by Puxkandl et al. (2002) has been useful in clarifying how fascia lengthens with stretching, with a clear effect at the cellular level, resulting in increased shear stress between the collagen fibres and an increase in length maintained through the adaptive viscous process. McHugh and Cosgrave (2010) reported that the stretching force had to be maintained long enough to maintain the gain once the force is removed. Our results are consistent with this view, with fascia beginning to creep after 4 min of intense stretching.

The need to hold a stretch for at least 4 min to obtain a physical increase in the length of a fascia has previously been reported (McHugh and Cosgrave, 2010; Rosario and Foletto, 2015; Germain and Regis, 2016). However, a Cochrane review failed to identify evidenced-based information on the optimal parameters of the required intensity of stretch and the hold time (Harvey et al., 2017). The tension, duration of application, amount of energy applied, joint mobility, and velocity of lengthening are parameters that can reveal the processes underlying the lengthening response of fascia during stretching (Germain and Regis, 2016; Zatsiorsky and Prilutsky, 2012; Gras, 2011). A low intensity stretch is insufficient to stimulate lengthening (Björklund et al., 2001); thus, in our study, we used force magnitudes ranging between 30 and 130 N m. We calculated that 10–35 J of stretching work is required to achieve a rate of lengthening of 2 mm·min⁻¹ (Fig. 2A–B), within an individual's tolerance to discomfort and pain (Fig. 2G–H). Moreover, the repetition of long duration stretches (11 sessions in our study, performed twice per week) seem to be necessary to achieve sustained length increases. In Fig. 5, we show a plausible mechanistic pathway by which repeated creep responses of the fascia could contribute to the measured increase in the length of the fascial compartment of the anterior thigh. This pathway was based on our findings and recent research on collagen biochemistry and biomechanics (Purslow, 2002; Puxkandl et al., 2002; Yoon and Halper, 2005; Scott and Orford, 1981; Redaelli et al., 2003; Szczesny et al., 2015; Fessel and Snedeker, 2009). As pain tolerance and maximal bearable tension did not change between stretch 1 and 11, we had to suggest a more mechanical explanation for the way fascia « records » the lengthening. Soft matter physics (De Gennes, 1971, 1975) may help a lot to suggest a new hypothesis to explain how the gel of glycosaminoglycans (GAG) can record the lengthening (Fig. 5). The Gel of GAGs would be a matrix to anchor the short GAG link to collagen1 (Fig. 5).

4.2. The physical reaction of fascia to high intensity stretching

The derivative $dT \cdot dt-1$ shows that passive fibres are likely to be recruited faster after 11 sessions of stretching (Fig. 4). Of note is that, after the 6-week program, the tissue reacted to stretching in a more homogenous fashion, indicating that the fascial network is likely to retain a memory of the usual strain applied. This strain memory would increase the mechanical resilience of the tissues, which might explain why long duration high intensity stretching provides a protective effect against overload injuries of tendons and muscles in athletes.

The lengthening achieved by our protocol likely resulted from a

dynamic reorganization of fascia to resist the applied strain, with the adaptive process becoming more efficient over time, from session 1 to 11, rather than from a change in elastic components, such as titin (Zatsiorsky and Prilutsky, 2012; Mow and Huiskes, 2005). As such, the measured changes are likely to have been dominantly contributed by the *fascia lata* rather than by the *rectus femoris*. An interesting point is that the number of taut fibres is the same in the first session and the 11th stretch (Fig. 4,A-B). Considering the three-dimensional organization of the collagen fibres in a fascial sheet (Reiser et al. (2017); Schleip et al., 2012; Mow and Huiskes, 2005; Purslow, 2002; Puxkandl et al., 2002), the greatest effect would be on the tauter fascial fibres within the network. In Fig. 6, we show how our results may be interpreted considering recent findings in the field of soft matter physics or biochemistry. We based Fig. 6 on Puxkandl model (2002) and De Gennes soft matter physics theory (1975) to explain the effect of repeated sustained stretching on a fascial network. The doubling in speed of recruitment of collagen fibres after 11 stretch sessions (Fig. 4 dT·dt-1) would explain why stretching increases stretch tolerance. If more fibres sustain the same tension, the Golgi sensors would be stimulated later and the repartition of the tension would be better. This indicates that each fibre sustains a lower amount of tension for the same length and that the Golgi sensors linked to these fibres are stimulated later when the fascia is lengthened further.

Our results may be better understood by considering that each collagen fibre in the GAGs gel reacts as a Maxwell body to the stretch. Collagen would be the main elastic compound while the GAGs would be the main viscous compound (Fig. 5). To illustrate this, it is useful to consider a 2009 study by Fessel and Snedeker, who observed that a low-quality network of GAGs would be sufficient to transmit small shear stress with short bout of low intensity stretching. They noticed the digested network of GAGs was insufficient under high shearing stress. This highlights the role of GAGs in providing an adequate anchor for the collagen fibres. The key equations for the physical response of a gel matrix (De Gennes, 1971, 1975) explain why the fascia becomes more robust when strain is applied fast, as during lengthening-shortening cycles of the fascia in a marathon.

The use of slow eccentric exercises, assessed by Roos, et Al (2004) for tendon healing, may facilitate a homogeneous response of all collagen fibres within a tendon or fascial network to an applied tensile force. Our findings are in agreement with those of this study.

Increasing the length of the anterior compartment (*fascia lata* and *rectus femoris*) produces a catapult-like effect in runners who stretch on a regular basis (Sawicki et al., 2009). In the same way, in our study, we identified that the catapult reaction increased to about 33% after the 11 stretches in our group (Fig. 4, C-D). This may be the reason why two participants reported feeling lighter during running after the stretching program.

4.3. Sensory adaptation

The subjective sensation of tension was the factor limiting the magnitude of the stretching force applied (Fig. 2C–D). As previously stated, we believe that the pain was associated with the creep response of the collagen fibres during the lengthening process, with an average increase of 0.7 mm achieved in each session, for an effective increase in length of 0.2%. (Fig. 2, G-H; Fig. 3).

Sensory adaptation to stretching, as previously described in some articles (Freitas et al., 2018; Wepler and Magnusson, 2010; Björklund et al., 2001), is unlikely to be a contributing factor in our results. The increase in pain and maximal bearable tension were similar during the 1st and the 11th session in our study. In all the previous studies, sensory adaptation was evaluated at short bouts

of low intensity stretching, which would influence the creep response of very few fibres within the fascial network. The apparent 33% increase in stretch tolerance during the first few seconds would reflect the reorganization of the same number of fibres, as stretch tolerance is exactly the same after 8 min of stretching (Fig. 2,C-D). As previously stated, however, as the collagen fibres creep inside the fascia lengthening it, the associated pain would also decrease for a particular length of the fascia. This decrease in pain, however, does not reflect sensory adaptation, but rather is an outcome of a change in the physical parameters of the fascia, well demonstrated by the derivative $dT \cdot dt^{-1}$. The Golgi sensors of the fascial structure would protect it from the overload of the taut areas of the fascial sheet, while free nerve endings would protect it from excessive creep (Fig. 6). This doesn't mean that there is no sensory adaptation but that the mechanical changes were so important in this experiment that it was impossible for us to evaluate it.

4.4. Limitations

The limitations of our study were as follows: First, as the pelvis was restrained with straps and an elastic cushion, there was the possibility of some movement of the pelvis, which might have contributed to an error in our measured force magnitude and rate of tensile force applied to the anterior compartment of the thigh (Fig. 1). We used photos to check the validity of the hip extension measured by the rope and the pulley system. Hip extension measured by the photos is presented Fig. 7. A second limitation is our selection of the *fascia lata*, which is the longest continuous fascial structure in the body (Jensen and Davy, 1975; Otsuka et al., 2018). Accounting for the wrapping path of the fascia lata (Germain and Regis, 2016; Zatsiorsky and Prilutsky, 2012; Mow and Huiskes, 2005), we can estimate that an increase of 12° in the hip range of motion would translate to a 2% increase in the length of the *fascia lata*. However, this calculation could not be reliably applied to shorter muscles and, therefore, the effect of stretching would be difficult to predict in these cases, particularly when we consider the limitations in the accuracy of the goniometric readings. Considering all the limitations of surface electromyography (Byrne et al., 2005), it was not useful to identify the contractile effects of the stretching. The activity of the *rectus femoris* and *fascia lata* was within the resting baseline levels. Therefore, we were unable to confirm a decrease in muscle activity with the prolonged stretch, as has been previously reported (Magnusson et al., 1996; Lin et al., 2008).

5. Conclusion

Maintaining adequate length of myofascial structures is important in athletes to offer protection against injury and to improve force output (Sawicki et al., 2009). We demonstrated the effectiveness of prolonged bouts of high intensity stretching in improving the rate of lengthening of a muscle within 11 sessions (with each session consisting of a 10-min bout of stretch). This increase in length, however, was not associated with a decrease in the discomfort and pain associated with this type of stretching. Our results, which provide evidence of the importance of incorporating high intensity stretching to improve the mechanical efficiency of muscle performance, would be of value to coaches (McHugh and Cosgrave, 2010; Thacker et al., 2004). For clinicians, the self-reported sensation of tension and pain should be carefully monitored during stretching, providing a reliable measurement of the magnitude of tension being applied to a tissue. Moreover, the positive response of the *fascia lata* to prolonged bouts of high intensity stretching indicates the benefit of this approach to

specifically increase the mechanical efficiency of this myofascial structure.

Clinical relevance

To lengthen fascia, clinicians should apply a high intensity tension for several minutes.

The fascia reacts more homogeneously after 11 stretches and the fascial sheet seems to be strengthened by repeated stretching sessions.

Lengthening speed, *in vivo*, is limited by the perception of tension.

Lengthening during a stretching session is limited by the perception of pain.

CRedit authorship contribution statement

Frank Germain: Data curation, Conceptualization, Methodology, Formal analysis, Writing - original draft. **Elodie Lemarchand:** Investigation, Data curation. **Raphael Perrin:** Formal analysis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbmt.2020.02.028>.

Disclosure statement

The authors have no conflicts of interest to declare.

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