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Geehoon Park, PhD
Matt Clark
Craig Cheney, PhD

Analyzing Muscles with the Pact Sense Scanner

Pact Sense, a Novel Muscle Mechanical Property Measurement Device

Impact Biosystems has developed a novel muscle measurement device that provides physical therapists, trainers, and athletes with important information on mechanical properties of muscle, which can be used to improve training and recovery.

Figure 1. The Pact Sense is a novel, hand-held, muscle scanner

The mechanical properties of muscles are an important indicator of the state of muscle. These properties can be subjectively evaluated by massaging the muscle by hand, and feeling, for example, the tightness of the muscle. Research has shown that the stiffness of a muscle is related to its performance [1], physical injuries (e.g. muscle tear) [2], and some diseases (e.g. Parkinson's and Hoffman's syndrome) [3]. High volume strength training results in an altered mechanical state of engaged skeletal muscle due to increased blood flow, increased blood perfusion, activated muscle contractile machinery, micro-tears in the muscle fibers, and increased local production of metabolites. Combined with the feeling of exertion and fatigue, muscle can feel stiff and tight during, and immediately after, a strength training session. Anecdotally, it is well understood by weight lifters that the degree to which the muscle is "pumped" correlates significantly with the intensity of the lift.

Additionally, professionals such as physical therapists and trainers routinely palpate their patient's muscles and use the mechanical state of the muscle to monitor exertion levels, injuries, and recovery. While muscle palpation is generally believed to give reliable and repeatable information to well-trained practitioners, the mechanical properties of the underlying tissues are often difficult to compare from one practitioner to another effectively, and to communicate with athletes and clients. This is mainly because palpation is a qualitative evaluation, and not a quantitative one.

Impact Biosystem has developed Pact Sense — a portable, handheld, muscle scanner that accurately measures the mechanical properties of muscle and soft tissue, and presents the results in a quantitative format that can lead to actionable feedback for optimizing an athlete's training and recovery. Pact Sense measures the muscle mechanical properties by delivering mechanical pulses into the surface of the skin and recording the way the underlying tissue responds. The collected data is processed using proprietary algorithms to calculate the mechanical properties of the muscle, which is displayed to a user through our mobile application.

This white paper presents the results of research studies performed by Impact Biosystems using the Pact Sense, which demonstrate its muscle measuring capabilities for various applications.

Pact Sense Parameters

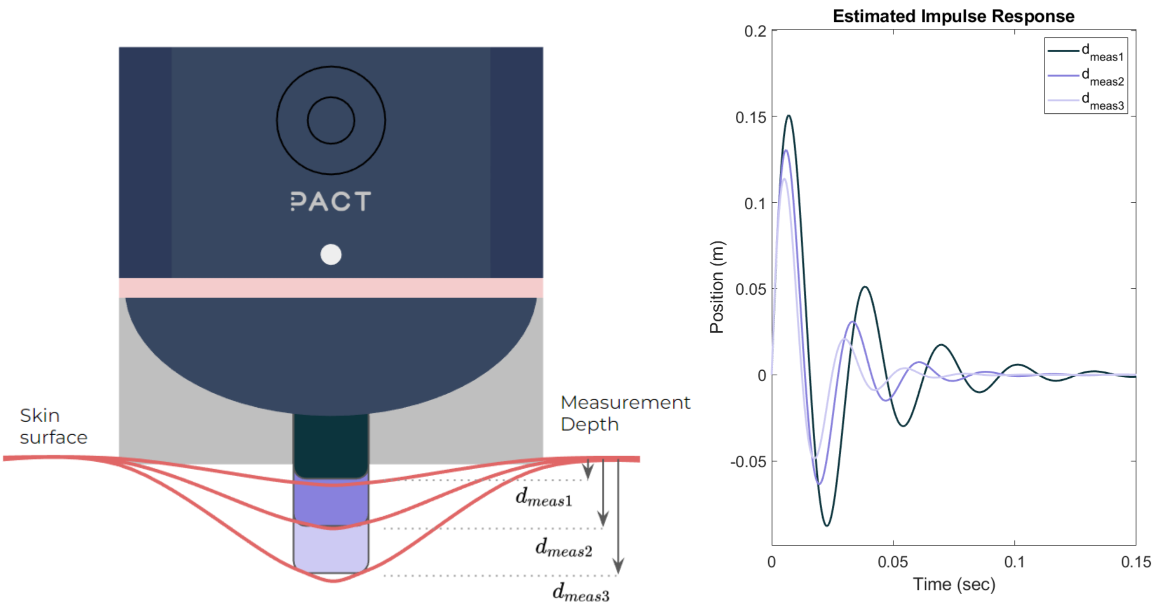

Figure 2. Illustration of how Pact Sense measures the muscle mechanical properties at 3 different measurement depths (left) and corresponding estimated impulse responses (right).

Our research shows that muscles and soft tissue can be modeled as a non-linear second order mechanical system, of which parameters are dependent on the depth of measurement. The depth dependency originates from a non-linear strain-stress relationship of biomaterials where the ratio between stress and strain increases at a higher strain [4]. To accurately characterize the mechanical system of a muscle with such a nonlinearity, Pact Sense measures the response of a muscle at different depths which is represented by the impulse response function shown in Figure We 2. The mechanical properties of the muscle, local inertia [kg], stiffness [N·m^{-1}], damping [N·s·m^{-1}], and damping ratio, are extracted from the impulse responses and used to generate Pact Sense parameters that describe the state of the muscle.

Figure 3 shows the extracted properties of relaxed biceps brachii of a 35 year old male measured by Pact Sense. The depth dependency of the extracted properties are reflected as linearly proportional relationships between measurement depths and the property values. Pact Sense parameters are derived from this relationship and used to describe the change of it when the state of the muscle changes. For example, Figure 4 describes the derivation of the parameters, ***Stiffness Slope*** and ***Stiffness***. The two stiffness curves shown in the figure are the Pact Sense measurement of the same biceps brachii from Figure 3 at relaxed (blue) and flexed (red) state. When the muscle is flexed or contracted, it becomes tighter, or stiffer, which is reflected as the measured stiffness curve at the flexed state located above that at the relaxed state. One of Pact Sense parameters, ***Stiffness***, is introduced to describe this change of the stiffness curve. It calculates how far the stiffness curve is located compared to the baseline (gray dotted line) to describe how the overall stiffness of the muscle changes. In addition, it is also important to note that the slope of the curve changes as the muscle contracts. Another Pact Sense parameter, ***Stiffness Slope***, calculates the slope of the curve to capture this change in the nonlinearity of a muscle's stiffness.

A similar algorithm is applied to the damping and damping ratio to generate other Pact Sense parameters: ***Damping Slope***, and ***Damping***. More detailed information of the Pact Sense Parameters is described in additional white papers published by Impact Biosystems.

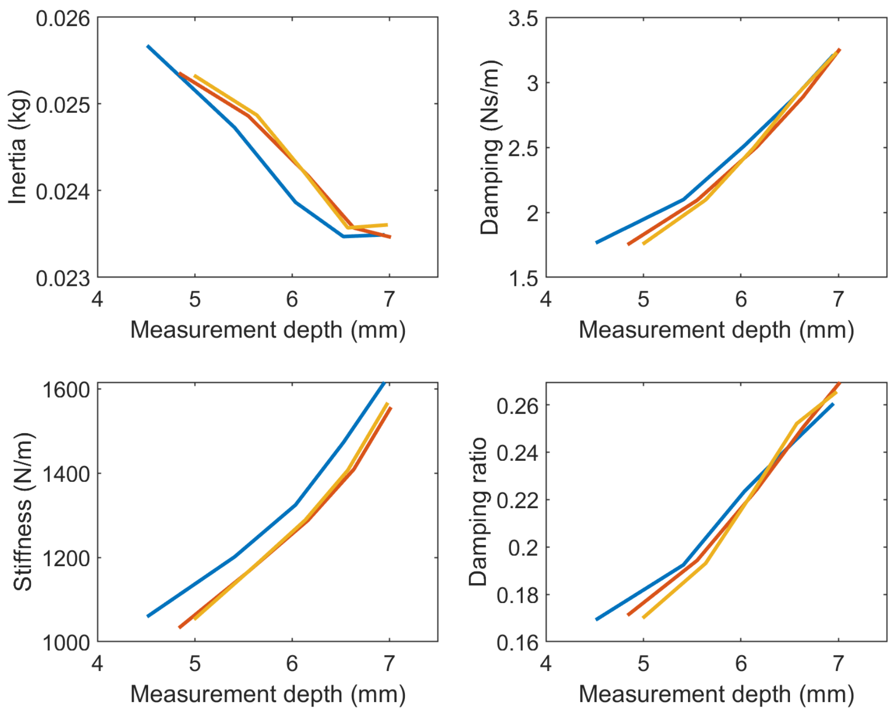

Figure 3. Muscle mechanical properties (inertia, damping, stiffness and damping ratio) of a relaxed biceps brachii measured by Pact Sense. Note that the measured properties are a function of the measurement depth into the tissue.

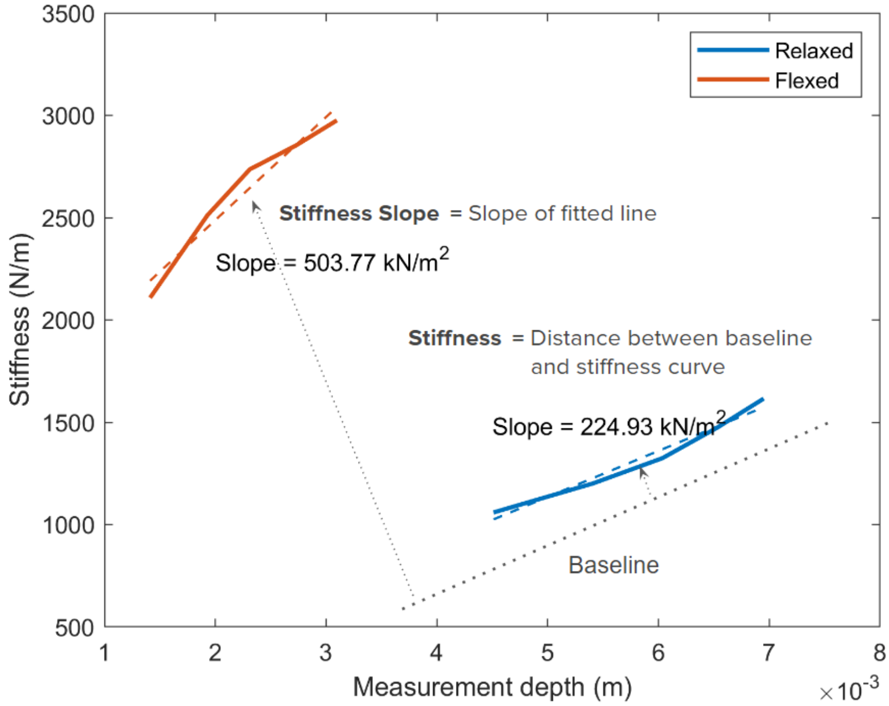

Figure 4. Stiffness-depth curve of a biceps brachii at relaxed (blue) and flexed (red) state measured by Pact Sense. Pact Sense parameter, ***Stiffness****, measures the distance between the stiffness curve and a baseline (gray dotted line). Another parameter,* ***Stiffness Slope,*** *is defined by the slope of a linear fit to the stiffness curve.*

Clinical Studies with Pact Sense

1. Change in Stiffness of a Muscle

Key Findings: Pact Sense can successfully measure the change in stiffness of a muscle.

One of the important mechanical properties that Pact Sense measures is the stiffness of a muscle. In physics, stiffness [$N{\cdot}m^{-1}$] is defined as "the extent to which an object resists deformation in response to an applied force" [5]. The stiffness of a muscle can be changed under many circumstances but the simplest way to change it is to contract (flex) your muscle, similar to how bodybuilders pose. Many researchers have shown that the stiffness of a muscle proportionally increases with the amount of muscle contraction; in other words, the amount of the generated force (see Figure 5). This is due to the muscle physiology that the increase of force is achieved by increasing the number of cross-bridges between actin and myosin filaments of your muscle which are tiny structures in a muscle that lie along the direction of the contraction.

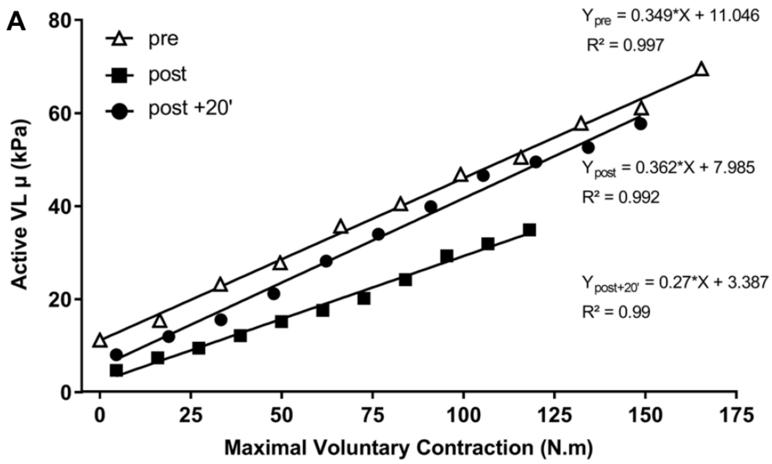

Figure 5. Changes in relationship between viscoelastic properties of the vastus lateralis muscle measured by shear wave elastography and absolute generated torque at pre- and post- workout. [6]

In this experiment, we invited 3 healthy, young adult participants to the Impact Biosystems lab to measure the stiffness of their biceps brachii using the Pact Sense while at rest, and while contracting the muscle at various contraction forces (10, 20, 30, 40, 50, and 60% of force at their maximum voluntary contraction). As shown in Figure 6, stiffnesses of the biceps measured by Pact Sense also show the same trend from the literature [6] that the stiffness increases linearly with the amount of force applied. This simple result demonstrates that Pact Sense can measure the known stiffness change of a muscle. Also the variation in the trend of the stiffness change potentially suggests the difference in the muscle properties between subjects which will further be investigated.

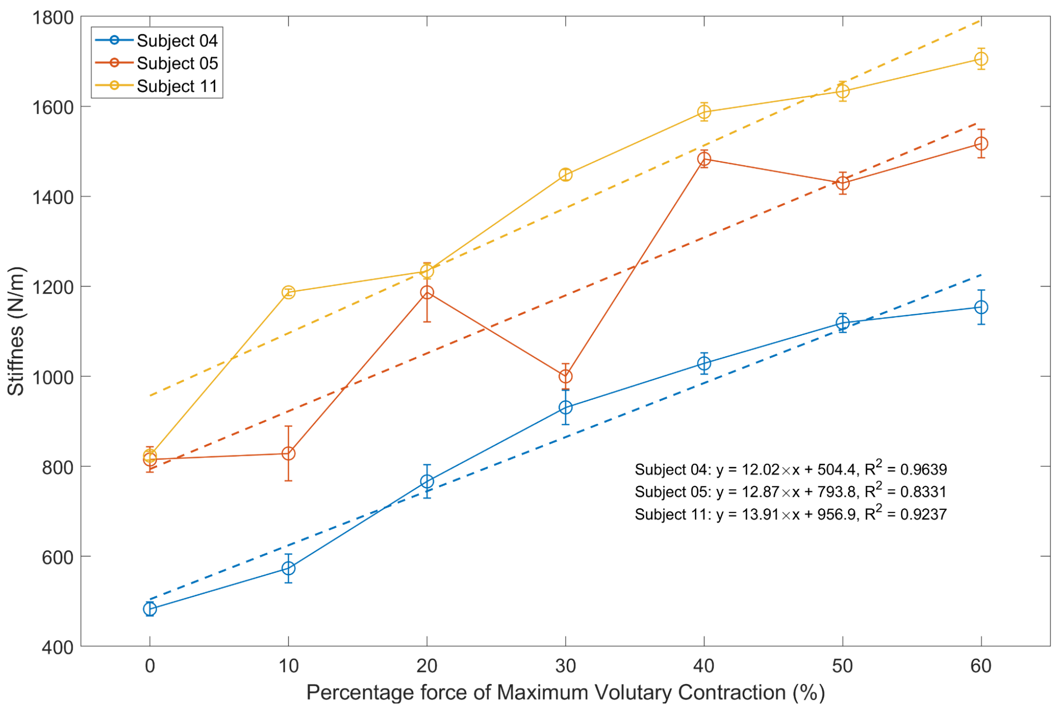

Figure 6. Changes in relationship between the stiffness of biceps brachii muscles measured by Pact Sense and percentage force of its maximum voluntary contraction.

2. Effect of Eccentric Biceps Curls on Stiffness of the Biceps

Key findings: The stiffness change during the workout measured by Pact Sense reflects the corresponding change in the physiology of a muscle.

The main objective of this study was to understand how the bicep brachii stiffness measured by Pact Sense is related to the blood flow and thickness change of the muscle during an intensive eccentric biceps exercise. A 35 year old male participant performed 6 sets of 10 repetitions of eccentric biceps curls using a dumbbell of 90% of 1 maximum repetition (1RM) weight. After each set, Pact Sense was used to monitor the change in the stiffness of the relaxed biceps every 5 min for 5 times. In addition, an ultrasound imaging device (Butterfly iQ+, Butterfly Network Inc.) was used to measure the blood flow change in the brachial artery and the thickness change of the biceps muscle with the same measurement frequency as Pact Sense.

As shown in Figure 7.a and 7.b, in the early sets of the exercise (set 1 and set 2), the blood flow peaks right after the end of the last curl and decreases back to the pre-exercise range, whereas in the later sets of the exercise, it remains slightly higher than the pre-exercise range without showing the pronounced peak. Also, the thickness of the muscle continuously increases as the exercise proceeds and reaches its steady state at around the 5th set, which is likely because of the elevated perfusion of the muscle in response to increasing exercise duration. Interestingly, the stiffness of the same muscle measured by Pact Sense reflects the drastic blood flow change during the earlier sets of the exercise (Figure 7.a) but eventually follows the trend of the muscle thickness during the later sets of the exercise (Figure 7.b).

The change in the blood flow and muscle thickness during anaerobic exercise have been explained as the body's effort to accommodate the increased needs of blood to support the muscle contraction [7-9]. The correlation between these physiological changes and the Pact Sense stiffness measurements demonstrates the device’s capability in detecting the change of the muscle property. Moreover, it opens up the possibility of using the device to monitor the intensity of a muscle exertion during the weight lifting exercise which will be measured as the increase in the stiffness of the muscle.

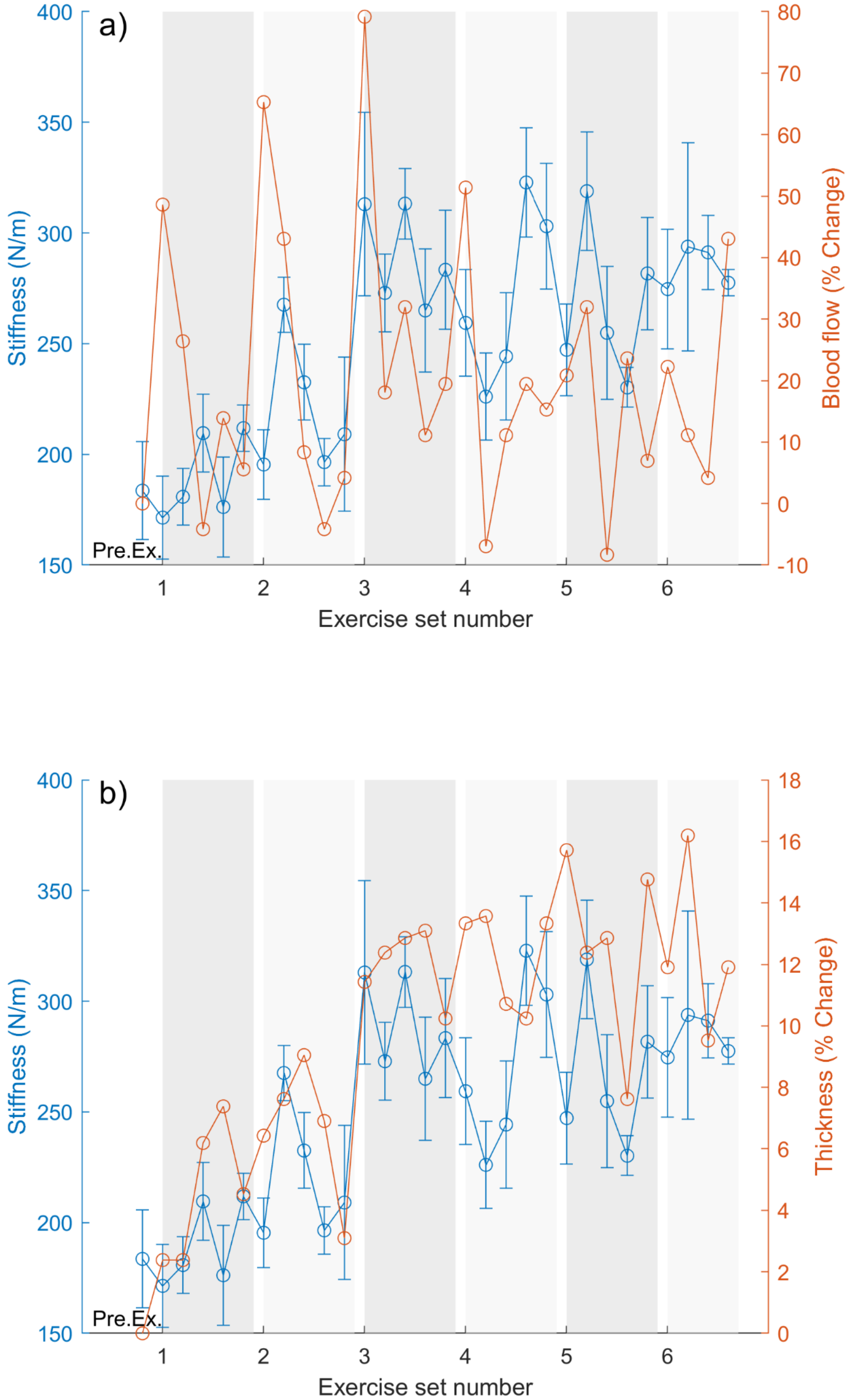

Figure 7. Stiffness changes of biceps measured by Pact Sense in response to 6 sets of eccentric biceps curls and corresponding change in a) blood flow of brachial artery and b) thickness of biceps belly measured by ultrasound imaging device.

3. Effect of Delayed Onset Muscle Soreness (DOMS) on Stiffness of a Muscle

Key findings: The development and progression of DOMS can be reflected as the change in the stiffness of a muscle measured by Pact Sense.

An intensive eccentric exercise is well known to induce DOMS, especially when it is conducted on individuals who are not used to the exercise [10]. In general, DOMS is understood as stimulation of the nerve system around a damaged muscle and/or connective tissue caused by the leakage of substances from the damaged tissue to extracellular space [10]. Also when DOMS is experienced in a muscle, the swelling of the muscle occurs which makes individuals experience the tightness in their muscle [11]. Impact conducted a study to monitor the development and progression of DOMS after eccentric exercise in the biceps brachii by measuring the stiffness change of the muscle using Pact Sense.

2 subjects (20-35, 1 male / 1 female) performed eccentric biceps curls with the similar protocol described in the previous section. Pact Sense was used to monitor the change of stiffness of the bicep muscles prior to exercise, after every 2 sets of curls, 1 hour following exercise and every day following the intervention for 10 days. Also, the muscle thickness, serum creatine kinase (CK) level in the subject's blood sample, and soreness level (0-10 scale) were monitored at the same measurement timing as Pact Sense measurements. The muscle thickness measurement was used to estimate the swelling of the muscle and/or connective tissues, and the CK activity level was measured to indicate the development and recovery of the damage in the muscle [12].

The delayed development of soreness shown in Figure 8.c indicates participants experienced DOMS symptoms. Their CK level also increased (see Figure 8.b) as a result of micro damage of the muscle caused by the eccentric exercise [11]. The stiffness change measured by Pact Sense (see Figure 8.a) also follows the trend of soreness and CK level increase. This increase in the stiffness is the result of a swollen muscle which is a well-known symptom of DOMS [11]. The swelling can be attributed to the inflammation occurring in the damaged site of the muscle and part of a recovery process. This result suggests that the stiffness change measured by Pact Sense can be used to quantitatively monitor the development and progression of DOMS symptoms. Furthermore, the capability of recovery monitoring means that the device can also be utilized to evaluate and develop different recovery methods by providing quantitative information on your muscle.

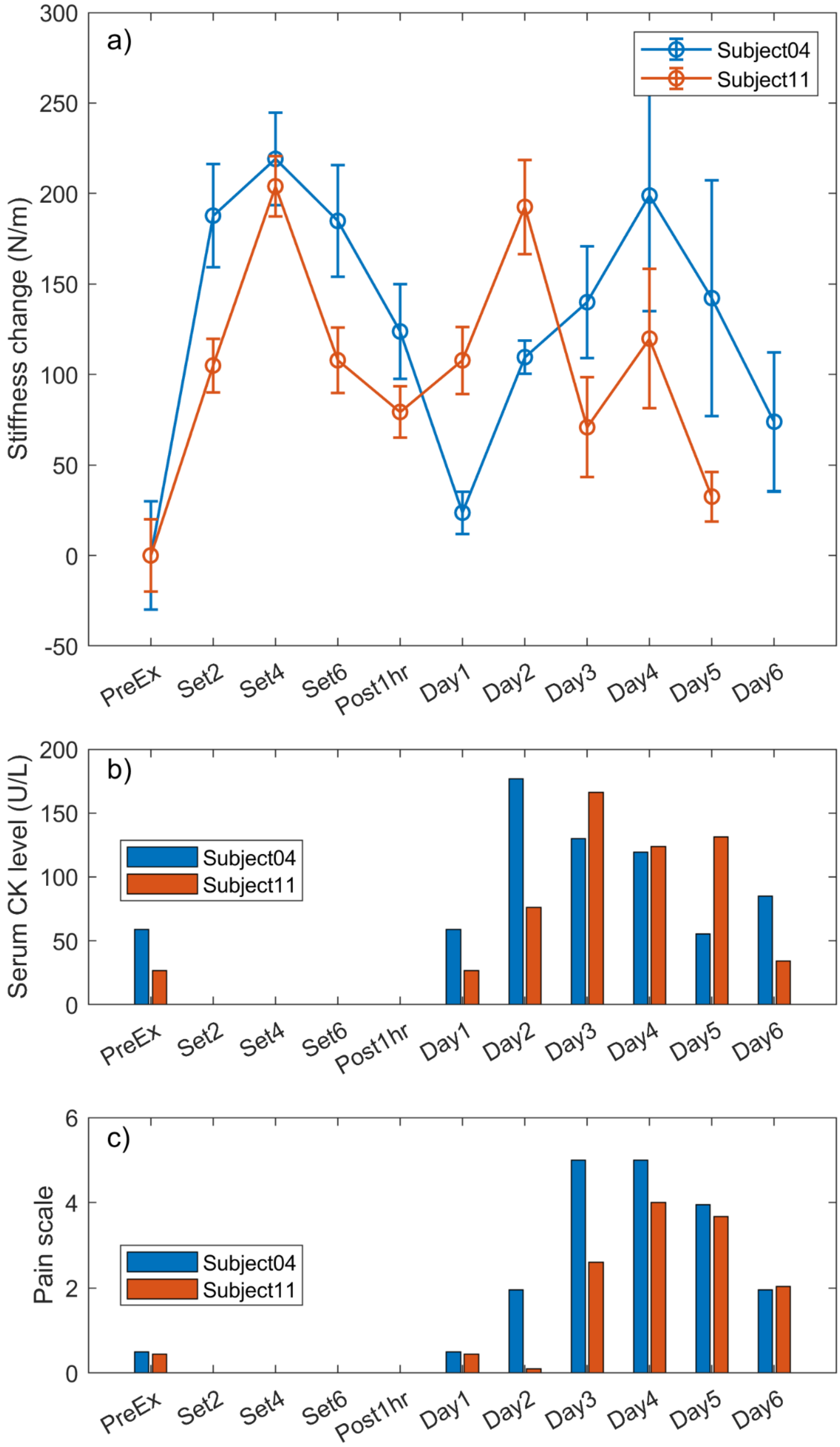

Figure 8. a) Stiffness changes of biceps measured by Pact Sense in response to 6 sets of eccentric biceps curls. b) Changes of serum creatine kinase level in blood samples measured before and after the curls. c) Changes of perceived pain level on a scale of 0-10 measured before and after the curls.

4. Effect of Cycling on Stiffness

Key findings: Pact Sense can provide feedback on the performance of exercise at muscle specific levels

Pact Sense has also been used to monitor the change of muscle state during a compound exercise. In this study, 3 subjects (20-35, 3 males) performed 3 sets of 20 min cycling on a stationary bike while maintaining their heart rate within 75% and 85% of their own maximum heart rate. Before this main exercise, all subjects went through 10 minutes of warm-up, cycling with 60% - 70% of their maximum heart rate. Stiffness changes of each subject's quads muscles, vastus medialis (VM) and rectus fermoris (RF), after every set and 1 to 5 days after the last exercise session were monitored by Pact Sense.

Figure 7 shows the change of stiffness on each muscle group of all the participants measured by Pact Sense. Most subjects show noticeable change in stiffness during the cycling sessions and after a few days from the exercise, similar to that observed in the eccentric exercise study. However, it is interesting to note that the trend of stiffness changes during and after exercise is different for each muscle and each subject. For example, the stiffnesses of VM for subject 21 (Figure 9.c) show distinct 2 peaks during the exercise (after the first ride) and the recovery from the exercise (2 days after the last ride), suggesting it went through a similar physiological change as the biceps muscle did in the eccentric exercise study. However, the stiffness change of RF shows a downward trend both during exercise and recovery. However, the opposite pattern of the change in stiffness can be found from the results of subject 5 (Figure 9.a), and subject 11 (Figure 9.b) that the stiffness was increased on VF but no significant change was observed on RF.

The decrease of stiffness measured by shear wave elastography after different types of exercise has also been observed in other research [6] indicating that the decrease has a strong correlation with the fatigue of a muscle. Based on this knowledge along with our measurements, the observed muscle specific trends of stiffness during and after the cycling exercise can be considered as the reflection of the different degree of muscle fatigue and swelling (as shown in

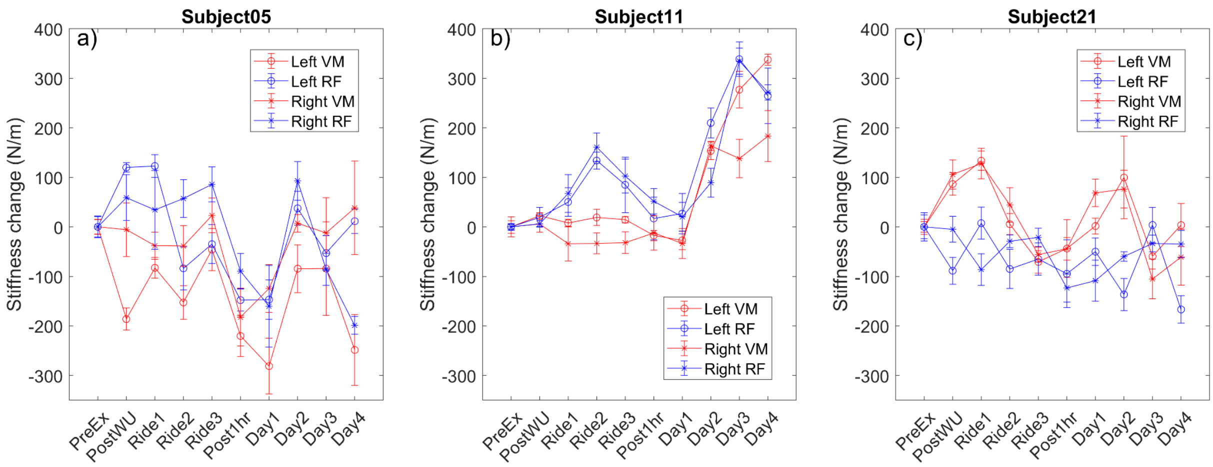

Figure 9. Stiffness changes of quads muscles (vastus medialis (VM) and rectus femoris (RF)) measured by Pact Sense, in response to warm-up (WU) cycling (10 min, 60% - 70% of maximum heart rate) and 3 sets of intensive cycling (20 min75% - 85% of maximum heart rate).

eccentric biceps curls study) occurring on each muscle group. This can potentially allow trainers and coaches to monitor the performance of their athlete at a much more detailed and sophisticated level than other conventional metrics such as heart rate.

5. Effect of Marathon on Stiffness

Key findings: Pact Sense muscle parameters can provide useful information that can add multiple dimensions to athlete's training and recovery.

The results from these clinical studies clearly demonstrate that Pact Sense can measure the change in the mechanical properties of a muscle when it goes through different exercises and the following recoveries. Trainers, coaches and athletes can use the measurement to monitor the effectiveness of their training and recovery methods as well as the development and management of injuries.

In addition, Pact Sense provides information on other mechanical properties such as stiffness slope, damping, and damping slope (see additional white papers published by Impact Biosystems for more detailed definitions of these parameters). Along with the stiffness of a muscle, these parameters also can be used to accurately assess the state of your muscle.

Figure 10 shows the change of the Pact Sense muscle parameters measured on calves muscles of an amateur marathon runner before and after a full-distance marathon event. Measurements of relaxed calves were taken 1 day before the event (Pre-Ex), 45 min after (Pos-45m), 4 hours after the event (Pos-4hr) and every morning after 1 to 30 days after the event. In a 2016 study [13], Andonian et. al. showed that the stiffness of quadriceps of runners measured by SWE decreases after they went through extreme mountain ultra-marathon (330 km mountain running during 72 hours). The graph shown in Figure 8.a also indicates that the stiffness of calves measured by Pact Sense decreased 45 min after the full-marathon event compared to measurements conducted before the event. The observed decrease in stiffness can be attributed to the fatigue of the muscles [6] and the following increase (Day1-2) in stiffness could indicate the recovery process of muscles due to the extreme exertion during the event as shown in Impact's DOMS study.

Other muscle parameters also responded to the exertion during the event as an increase in case of stiffness slope and damping slope as shown in Figure 10.c, 10.d, and 10.e. However, the damping parameter shown in Figure 10.b decreases 45 min after the event and during the recovery up to 4 days after the event. These results can possibly suggest that multiple physiological changes occurred in the calf muscle as all the parameters are independent from each other.

The change of parameters shown after the participant resumed training is also important to note (Figure 11). The participant took rest for 4 days without any exercises or serious activities to recover from the event and began to exercise again slowly ramping up the intensity of the training throughout several weeks. The damping of the calves on both sides responded significantly to this new event resulting in a significant decrease. Furthermore, the change of stiffness, stiffness slope, and damping slope varies dramatically from left to right reflecting the asymmetry of the participant's calves. For example, the stiffness slope of the left calf began to plunge 2 days after the participant resumed training whereas that of the right calf continued to increase following its previous trend. In fact, the participant had been experiencing soreness and pain on the left calf muscle throughout the training period of the marathon as well as after the marathon, which we hypothesized as the reason for the observed differences within the measured parameters on both sides.

The research team at Impact Biosystems is focusing on learning and understanding more about meanings of the Pact Sense parameters with regards to muscle performance, level of muscle exertion, muscle damage, and injuries through on-going clinical studies and collaborative research with external research groups. These follow-up studies and research will allow us to provide richer and more digestible interpretations of measurements from athlete's daily life, such as those from this longitudinal study. Furthermore, this knowledge will help trainers and coaches develop more efficient and effective actionable feedback for their athletes.

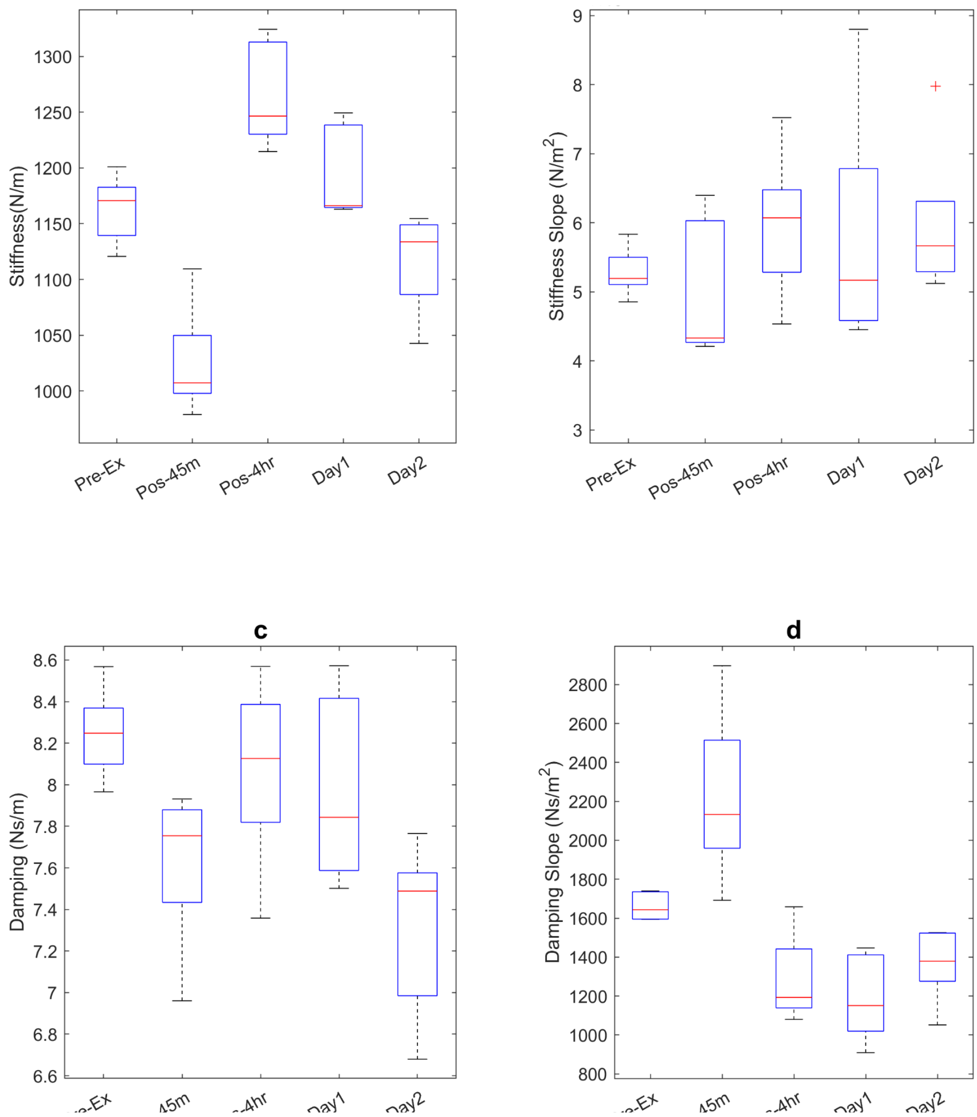

Figure 10. Change of Pact Sense parameters (a) stiffness, b) stiffness slope, c) damping, d) damping slope and e) elasticity observed in the left calf muscle before (Pre-Ex) and after (post 45 min, post 4 hr, post 1 day, and post 2 day) the full marathon event.

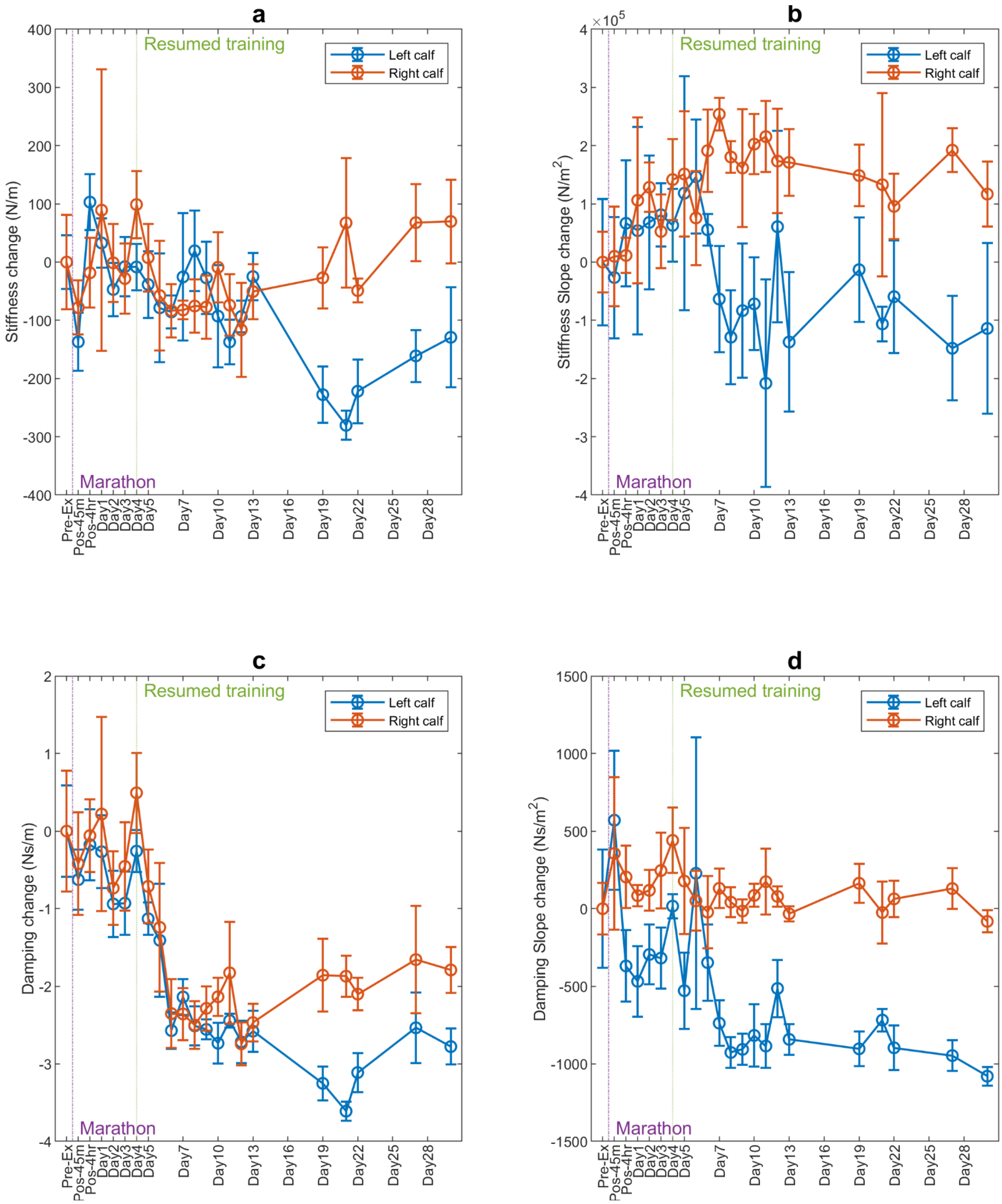

Figure 9. Change of Pact Sense parameters (a) stiffness, b) stiffness slope, c) damping, and d) damping slope) observed in the left calf muscle before (Pre-Ex) and until 30 days after the full marathon event.

Conclusion

This white paper demonstrates that Pact Sense can successfully measure the stiffness of a muscle by replicating the well-known relationship between the amount of contraction of a muscle and corresponding stiffness. Additionally, it shows the relationship between the stiffness of biceps measured by Pact Sense and the physiological change of the muscles during and after the intensive anaerobic exercise proving its capability of monitoring the muscle exertion level during the exercise and recovery from the following DOMS. Pact Sense was also used to monitor the change of a muscle in compound exercises such as cycling and running, showing it can provide detailed states of a specific muscle based on their stiffness measurements as well as other parameters (stiffness slope, damping, and damping slope). The results from these research show the potential of the device to improve the quality and efficiency of athlete's training and recovery.

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