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The Effect of Lateral Epicondylitis on Upper Limb Mechanical Parameters

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Abstract

Background—Lateral epicondylitis is a prevalent and costly musculoskeletal disorder characterized by degeneration of the common extensor tendon origin at the lateral epicondyle. Grip strength is commonly affected due to lateral epicondylitis. However, less is known about the effect of lateral epicondylitis on other functional parameters such as ability to react to rapid loading.

Methods—Twenty-nine lateral epicondylitis participants and ten controls participated in a case-control study comparing mechanical parameters (mass, stiffness and damping), magnetic resonance imaging signal intensity and grip strength of injured and uninjured limbs. A mixed effects model was used to assess the effect of dominance and injury on mechanical parameters and grip strength.

Findings—Significant effect of injury and dominance was observed on stiffness, damping and grip strength. An injured upper limb had, on average, 18% less stiffness ($p < 0.01$, 95% CI [9.8%, 26%]), 21% less damping ($p < 0.01$, 95% CI [11%, 31%]) and 50% less grip strength ($p < 0.01$, 95%

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CI [37%, 61%]) than an uninjured upper limb. The dominant limb had on average 15% more stiffness ($p < 0.01$, 95% CI [8.0%, 23%], 33% more damping ($p < 0.01$, 95% CI [22%, 45%]), and 24% more grip strength ($p < 0.01$, 95% CI [6.6%, 44%]) than the non-dominant limb.

Interpretation—Lower mechanical parameters are indicative of a lower capacity to oppose rapidly rising forces and quantify an important aspect of upper limb function. For individuals engaged in manual or repetitive activities involving the upper limb, a reduction in ability to oppose these forces may result in increased risk for injury or recurrence.

Keywords

lateral epicondylitis; tennis elbow; upper limb function; mechanical parameters; hand dominance

1 Introduction

Lateral epicondylitis (LE) is a prevalent and costly musculoskeletal disorder involving the common extensor tendon origin at the lateral epicondyle (Fan et al., 2009; Silverstein et al., 1998). It is characterized by microtears, collagen degeneration and angioblastic proliferation of the extensor tendon (Kraushaar and Nirschl, 1999). It is associated with repetitive forceful exertions of the forearm (Fan et al., 2009), affects 5–15% of the working population, is equally prevalent in women and men (Shiri et al., 2006) and is more prevalent in the dominant arm (Shiri et al., 2007). Pain at the lateral aspect of the elbow is a primary symptom of LE. In addition, gripping is often impaired and activities of daily living may be difficult to perform (Hong et al., 2004).

Clinical examination of patients with LE often includes assessment of grip strength and pain severity (Alizadehkhayat et al., 2009). While important, these measures do not provide information about other important aspects of upper limb function that may be affected by LE, such as reaction time or ability to react to rapid loading. For example, LE participants had longer reaction times than uninjured controls (Bisset et al. 2009). Alizadehkhayat et al. (2009) recommended assessment of the muscle balance of wrist muscle groups for functional recovery. Such evidence highlights a need to investigate other aspects of upper limb function which may be affected by LE.

A biodynamic model of the upper limb (Lin et al., 2001) has been previously used to evaluate the ability of individuals to react to rapid loading (Chourasia et al., 2009; Sesto et al., 2004; Sesto et al., 2008). The model represents the hand and arm as a single mass, spring and damper. Dynamic mechanical parameters of effective mass, stiffness, and damping are related to muscle-tendon capacity to react to rapid forceful loading. These parameters are important for function since they counteract the effects of applied loads (Lin et al., 2001; Sesto et al., 2006). Our laboratory has developed an apparatus to quantify dynamic mechanical parameters of the upper limb (Lin et al., 2001; Sesto et al., 2008). The apparatus delivers a harmonic sinusoidal rotation that is transmitted to the hand and arm through a handle that the participant grasps. The motion of the system changes when the hand is coupled with the system through the handle. Since the apparatus has known mechanical parameters (stiffness, damping, and effective mass), any change in the system response can be attributed to the person coupled to the handle. This apparatus was used in the current study to investigate the mechanical parameters of the upper limb of participants with LE and healthy, uninjured controls.

Research to date has investigated biomechanical changes in individuals exposed to varying intensities of short duration eccentric exercise (Prasartwuth et al., 2005; Semmler et al., 2007; Sesto et al., 2005a; Sesto et al., 2005b; Sesto et al., 2008) and workers with symptoms characteristic of LE (Sesto et al., 2006). While eccentric exercise is used to model skeletal

muscle injury (Lieber and Friden, 1999), none of these studies involved patients with a diagnosed tendon condition nor confirmed anatomical changes in the extensor tendon.

Magnetic resonance imaging (MRI) has been previously used to evaluate the degeneration of the common extensor tendon origin in LE patients (Potter et al., 1995; Savnik et al., 2004) but concomitant biomechanical changes have not been evaluated. For those with LE, MRI scans show areas of high signal intensity in the common extensor tendon origin and these areas correspond to mucoid degeneration and neovascularization (Kijowski et al., 2005). No previous studies have examined if reductions in upper limb mechanical parameters are observed in LE patients with confirmed tendon degeneration compared to the general population.

The objective of this study was to model the effect of upper limb injury on mechanical parameters and grip strength while accounting for limb dominance, sex, and age using data collected from male and female LE participants with unilateral and bilateral injury as well as healthy, uninjured controls.

2 Methods

2.1 Experiment Design

This study compared the mechanical parameters and grip strength of injured and uninjured limbs using data collected in LE participants (+LE) and healthy, uninjured controls (−LE). Mechanical parameters were collected bilaterally and MRI scans of the dominant limb for the −LE group and injured limb(s) for the +LE group were taken.

2.2 Participants

A total of 31 individuals diagnosed with LE were recruited from various outpatient clinics in a Midwestern city from June 2009 to February 2010. Two participants were excluded because of concurrent upper limb injury. Of the 29 eligible participants, 14 had unilateral symptoms, while 15 had bilateral symptoms. Diagnostic criteria for LE included tenderness to palpation over the lateral epicondyle and/or extensor mechanism and pain present on at least two of the following provocation tests: pain with resisted extension of the wrist or fingers, pain with resisted supination, pain with passive stretch to the wrist extensors or supinator. Ten healthy, uninjured participants were recruited from the university campus during the same time period. Participants in the −LE group were excluded if they reported upper limb symptoms.

All participants completed additional screening; those with coexisting or previous medical history of rheumatoid or inflammatory arthritis, chronic pain diagnoses, diabetes mellitus, pregnancy, systemic nervous disease, neuropathy, or acute trauma to the fingers or hands were excluded. Additional exclusion criteria include prior upper limb injury, concurrent upper limb injury, unresolved litigation and co-morbidities that could interfere with ability to participate in the study.

Participants received a detailed explanation of the study prior to informed consent being obtained in accordance with the university human subjects institutional review board. Demographics for the eligible study sample are presented in table 1.

2.3 Measurement of mechanical parameters

Measurement of the mechanical parameters was performed using a custom built free vibration apparatus (Lin et al., 2001; Sesto et al., 2008). Participants were seated on an adjustable height chair with back support. The shoulder, forearm and wrist were positioned

in a neutral position with the elbow flexed at 90°. The axis of rotation for the free vibration apparatus was aligned with the axis of elbow rotation to allow estimation of mechanical parameters applicable to supination and pronation of the elbow. The upper limb was stabilized against the body using a Velcro strap. All participants were instructed to grip the handle of the apparatus as hard as possible without pain and inhibit the oscillations by trying to maintain the handle in its neutral position.

When the participant resists the oscillatory motion by grasping the handle, the frequency and damping of oscillation is changed, and from this the mechanical parameters of the limb may be estimated. The equation of motion that describes the free vibration response of this system is: (Lin et al., 2001)

$$J\ddot{\theta} + c\dot{\theta} + k\theta = 0 \quad (1)$$

where, J = mass moment of inertia, c = damping constant, k = torsional stiffness, θ = angular displacement.

The total mass moment of inertia J is made up of components contributed by the participant ($J_{participant}$), the applied mass (J_{mass}), and the device itself (J_{device}). $J_{participant}$ is calculated using the conservation of momentum principle. The angular velocity of the free vibration apparatus is measured over 10 ms prior to the engagement of the participant with the apparatus (ω_1) and 10 ms after (ω_2). As J_{mass} and J_{device} are known, the moment of inertia for the human operator may be calculated using the following formula.

$$(J_{device} + J_{mass})\omega_1 = (J_{device} + J_{mass} + J_{participant})\omega_2 \quad (2)$$

The average calculated over eight repetitions was used. The natural frequency of oscillation (ω_n) of the system is:

$$\omega_n = \sqrt{(k_{participant} + k_{device}) / (J_{subject} + J_{device} + J_{mass})} \quad (3)$$

The torsional stiffness ($k_{participant}$) may be estimated by manipulating J_{mass} and k_{device} to achieve specific natural oscillation frequencies and using the known J_{device} and estimated $J_{participant}$ to fit the slope k to the linear relation between J and a function of ω_n :

$$J_{mass} = (k_{device} + k_{participant}) \frac{1}{\omega_n^2} - (J_{device} + J_{participant}) \quad (4)$$

Four natural oscillation frequencies of 2.81, 3.00, 3.24 and 5.30 Hz and two repetitions at each frequency were used to calculate the torsional stiffness.

Once J and k have been calculated, the damping constant (c) may be calculated using the formula

$$c = 2\zeta \sqrt{kJ} \quad (5)$$

where, ζ = damping ratio, measured from oscillations of the apparatus

Handle rotation was measured using an Allen Bradley Encoder 844B-Z405-D1024 (Rockwell Automation, Milwaukee, WI, USA) angle encoder. Sampling rate was 1000 samples/s. The period of oscillation ranged from 4 s to 17 s depending upon the stiffness and inertia of the apparatus and the human operator. The first two cycles were used for calculation of mechanical parameters for all participants.

The device has shown strong reliability and validity. A strong correlation (0.9) between measured and predicted frequency of oscillation based on previously measured mechanical parameters and less than 5% variation over 24 hours in mechanical stiffness values for controls have been reported (Lin et al., 2001; Sesto et al., 2004).

2.4 Measurement of pain-free grip strength

Assessment of pain-free grip strength was completed with participants seated in a chair with the shoulder flexed at 90°, the elbow extended and the forearm in the neutral position. This posture has been recommended for evaluation of grip strength in LE patients (De Smet et al., 1998; Dorf et al., 2007). All participants were instructed to squeeze the BASELINE® (Fabrication Enterprises Inc., White Plains, NY) dynamometer and cease squeezing prior to the onset of pain. Pain-free grip strength is a reliable measure (ICC=0.97) (Smidt et al 2002) of hand function in individuals with LE and is considered a better measure to assess sensitivity to change than maximal grip strength (Stratford et al., 1987). The grip span on the dynamometer was set at 4 inch. Three replications with 60 s intervals were performed bilaterally. The average of the three replications was used as the pain-free grip strength.

2.5 Magnetic Resonance Imaging

MRI examination was performed for all participants using an Artoscan 0.17 T limb scanner (GE Healthcare, Milwaukee, WI). Axial and coronal T1-weighted and fluid sensitive short tau inversion recovery (STIR) sequences of the elbow were used for semi-quantitative assessment of disease severity. T1 weighted scan parameters were: TR = 2050 ms, TE = 18 ms, Slices = 7, Gap = 1.0 mm, Thickness = 3.5 mm, Readout FOV = 180, Encoding FOV = 180, Samples = 192, Encoding # = 192. STIR scan parameters were: TR = 2050 ms, TE = 34 ms, TI = 75 ms, Slices = 7 Gap = 1.0 mm, Thickness = 3.5 mm, Readout FOV = 180, Encoding FOV = 180, Samples = 192, Encoding # = 192. MRI examinations were reviewed by a musculoskeletal radiologist who was blinded to group status. The grading scale used to assess the severity of chronic degeneration and pathologic changes in the common extensor tendon origin has been used in other studies of LE (Steinborn et al., 1999; Rabago et al., 2010; Walton et al 2011). This scale has been found to have good reliability (average intra-observer agreement = 79.4%) for the assessment of LE severity (Walton et al 2011). The grading scale is as follows:

- Grade 0 = Normal common extensor tendon which is of uniform low signal intensity on T1-weighted and STIR images.
- Grade 1 = Common extensor tendon with mild tendinopathy which is thickened and has intermediate signal intensity on T1-weighted and STIR images
- Grade 2 = Common extensor tendon with moderate tendinopathy which is thinned and shows focal areas of intense fluid-like signal intensity on STIR which comprise less than 50% of the total cross sectional diameter of the tendon.
- Grade 3 = Common extensor tendon with severe tendinopathy which is thinned and shows focal areas of intense fluid-like signal intensity on STIR images which comprise more than 50% of the total cross sectional diameter of the tendon.

2.6 Pain Intensity

All participants were asked to rate the average pain intensity in each of their elbows over the previous week using a visual analog scale (VAS) ranging from “0 = no pain” to “10 = most pain”. Note that for the purposes of ascertaining whether a participant was unilaterally or bilaterally injured, a limb was considered injured if the VAS score was greater than 0.

2.7 Statistical Analysis

The prespecified primary analysis of the mechanical parameters was a mixed effects linear model of the form:

$$\log(MP_{ij}) = \mu + \alpha_i + \beta_{Dom} D_{ij} + \beta_{Inj} I_{ij} + \alpha_{i,Inj} I_{ij} + \varepsilon_{ij}$$

with additional terms (not shown) to account for sex and age. Here, the response and covariates are

MP_{ij} = mechanical parameter of interest in participant i , limb j

D_{ij} = indicator that limb j is participant i 's dominant limb

I_{ij} = indicator that limb j in participant i is injured (pain intensity VAS > 0) and the fixed effect parameters are

β_{Dom} = fixed effect of dominance on MP

β_{Inj} = fixed effect of injury on MP

Random effects α_i and $\alpha_{i,Inj}$ are included to account for participant-to-participant variation in MPs and participant-to-participant variation in injury severity. The same model was used for the assessment of grip strength.

The mixed effects model permits simultaneous fitting of data for +LE participants with bilateral and unilateral injury and -LE uninjured controls to simultaneously estimate the independent effects of limb dominance and injury. Log transformation of the response was pre-specified based on the observed distribution of pilot data (Sesto et al., 2006). The back-transformed effects $100 * (e^{\beta_{Dom}} - 1)$ and $100 * (e^{\beta_{Inj}} - 1)$ are interpreted as respectively (1) the mean percent difference in the MP for dominant and non-dominant limbs and (2) the mean percent change in MP induced by injury.

In a post-hoc analysis, a similar mixed effects model was fit to injured limbs only (VAS>0) to examine the relationship between MPs (and grip strength) and pain intensity VAS scores:

$$\log(MP_{ij}) = \mu + \alpha_i + \beta_{Dom} D_{ij} + \beta_{VAS} VAS_{ij} + \alpha_{i,VAS} VAS_{ij} + \varepsilon_{ij}$$

Here, $100 * (e^{\beta_{VAS}} - 1)$ may be interpreted as the mean percent change in MP associated with each unit increase in VAS score in an injured limb.

Data analysis was conducted using the R language and environment for statistical computing (2010).

2.8 Sample size calculation

Based on pilot data collected on healthy individuals and participants with symptoms characteristic of LE (Sesto et al., 2006), simulated power calculations showed that a mixed effects analysis of $n=50$ participants, would have 90% power at $\alpha=0.05$ to detect an

injury effect of a 10% change in stiffness, the mechanical parameter of primary interest. Ultimately, n=39 eligible participants were recruited, 29 +LE participants and 10 -LE controls.

3 Results

3.1 Mechanical parameters

Table 2 provides summary statistics for mechanical parameters, grip strength, and MRI scores by limb with participants grouped by nature of injury: uninjured (-LE) participants, +LE participants with unilateral injury to the dominant limb, and +LE participants with bilateral injury. (The two participants with unilateral injury to the non-dominant limb are not included in this table.) The boxplots in Figure 1 show the distribution of mechanical parameters and grip strength by nature of injury. Each pair of boxplots shows the distribution of the parameter in dominant and non-dominant limbs. Stiffness, damping, and mass moment of inertia all show a dominance effect (more stiffness, damping, and mass in the dominant limb) among uninjured participants. In comparison, participants with dominant limb injury show an attenuation or reversal of the dominance effect as a result of injury for their stiffness and damping parameters, while bilaterally injured participants retain a dominance effect similar to uninjured participants but have comparatively less stiffness and damping in both limbs. The distribution of mass moment of inertia appears unaffected by injury.

The mixed effects model using log-transformed response was used to assess the effects of LE injury and dominance on stiffness, damping, and mass moment of inertia. (Note that this model included terms to adjust for sex and age, as well as allowing assessment of the effect of injury while accounting for limb dominance and vice versa.) Significant effects of LE injury were observed for stiffness and damping: an injured limb had, on average, 18% less stiffness ($p < 0.01$, 95% CI [9.8%, 26%]) and 21% less damping ($p < 0.01$, 95% CI [11%, 31%]) than an uninjured limb after accounting for effect of dominance. The effect of injury on mass moment of inertia was not significant ($p > 0.9$). Significant effects of limb dominance were also observed for all three parameters. A dominant limb had, on average, 15% more stiffness ($p < 0.01$, 95% CI [8.0%, 23%]), 33% more damping ($p < 0.01$, 95% CI [22%, 45%]), and 20% more mass moment of inertia ($p < 0.01$, 95% CI [5.3%, 36%]) than a non-dominant limb after accounting for effect of injury.

The appropriateness of the pre-specified log transformation was assessed. Shapiro-Wilk tests rejected normality for untransformed stiffness, damping, and effective mass ($p = 0.001$, 0.0005, and 0.002 respectively), but log-transformed responses passed the normality test ($p > 0.3$ in all cases). However, assessment of absolute effects of injury would allow better comparison to previously published results, so in a post-hoc analysis, the model was re-fit without the log transformation. The effect of injury (after adjusting for sex, age, and limb dominance) was a decrease in stiffness of 3.2 N m/rad ($p < 0.01$, 95% CI [1.6, 4.9]) and a decrease in damping of 0.0072 N m s/rad ($p < 0.01$, 95% CI [0.0037, 0.011]) (Figure 1). As before, there was no significant effect on effective mass.

3.2 Grip Strength

Table 2 provides summary statistics and Figure 1 shows the distribution of grip strength by nature of injury. The mixed effects model using log-transformed response was used to assess the effect of LE injury on grip strength adjusted for sex and age. Significant effects of both injury and dominance were observed. An injured limb exhibited, on average, a 50% reduction in grip strength ($p < 0.01$, 95% CI [37%, 61%]) compared to an uninjured limb after

adjusting for limb dominance. A dominant limb had, on average, a grip strength 24% higher ($p<0.01$, 95% CI [6.6%, 44%]) than the non-dominant limb after adjusting for limb injury.

The distribution of the grip strength data and model diagnostics called into question the adequacy of the pre-specified log-transformation for grip strength, and the model was also fit to grip strength without the log transformation in a post-hoc analysis. This showed that an injured limb had 160 N less grip strength ($p<0.01$, 95% CI [106, 213]) than an uninjured limb (adjusted for limb dominance), while a dominant limb had 40 N more grip strength ($p=0.02$, 95% CI [6.9, 74]) than a non-dominant limb.

3.3 Pain Intensity

All participants in the -LE group reported a pain intensity visual analogue scale (VAS) score of 0 in both limbs. Participants in the +LE group reported a pain intensity VAS score of 0 in uninjured limbs (by definition) and an average pain intensity VAS score of 4.64 (SD=2.30) in injured limbs.

In a post-hoc analysis, a mixed effects model was fit (to only injured limbs) to ascertain the relationship between pain intensity VAS scores and mechanical parameters / grip strength in injured limbs. Each unit increase in VAS score was associated with a mean decrease in stiffness of 5.7% ($p<0.01$, 95% CI [3.5%, 7.9%]) corresponding to an absolute decrease of 0.67 N m/s, ($p<0.01$, 95% CI [0.35, 1.00]) in an injured limb but no statistically significant change in damping or mass moment of inertia. For grip strength, the model fit without the log transformation was highly significant ($p=0.002$) and showed that a unit increase in VAS score was associated with a mean 34 N decrease in grip strength (95% CI [20, 47]).

3.4 MRI

MRI scans were performed on all participants in the -LE group and 28 participants in the +LE group. Results from the more injured limb of the bilaterally injured +LE participants are used. One participant in the +LE group declined the MR scan. For participants in the -LE group, none showed an increased signal intensity in the common extensor tendon and therefore were assigned a score of 0. All participants in +LE group had increased signal intensity in the common extensor tendon region. Eight +LE participants were assigned a score of 1, ten were assigned a score of 2 and ten were assigned a score of 3.

No adverse events were reported during testing.

4 Discussion

This study investigated the effect of LE on upper limb mechanical parameters and grip strength. A significant effect of LE was observed for stiffness (18%) and damping (21%) and pain-free grip strength (50%). Positive MRI results observed in all +LE participants confirmed the clinical diagnosis of LE. No participant in the -LE group demonstrated increased signal intensity in the common extensor tendon.

Our previous research has shown similar short term reduction in mechanical parameters following short duration eccentric activity (Chourasia et al., 2009; Sesto et al., 2004, Sesto et al., 2008). Eccentric activity is associated with myofibrillar disruption (Lieber et al., 1991) which was considered to be the cause of reduction in mechanical parameters. Repeated eccentric activity is also the primary cause of microtears in the common extensor tendon and the subsequent cellular response is considered to cause LE (Kraushaar and Nirschl, 1999). The ability of the forearm muscles to generate force and the ability of tendon to transmit force can both affect the mechanical parameters. Therefore, it is reasonable to expect a

reduction in mechanical parameters for LE patients due to the degeneration of the common extensor tendon.

It is plausible that pain may also affect the mechanical parameters in +LE participants by limiting their ability to grip the free vibration apparatus. However, the motivation of the participants may be less affected if a pain free measurement is performed (Kennedy et al 2010). Pain-free grip strength is commonly assessed in participants with LE (Stratford et al. 1987; Smidt et al 2002; Bisset et al 2006). In the current study participants did not report pain during measurement of mechanical parameters but the effect of pain on mechanical parameters is unknown.

The primary statistical analysis was prespecified based on preliminary data collected in male workers with symptoms characteristic of LE (Sesto et al., 2006). These data indicated large inter-participant biological variation relative to between-limb variation within participants and indicated that a mixed effects model fit to both limbs in all participants (+LE and -LE groups) would have more power to detect an effect than a group comparison of injured limbs in +LE participants to healthy limbs in matched -LE controls. This approach permits simultaneous estimation of the effect of limb dominance and limb injury. The log transformation of parameters was also prespecified and was based on observed increases in parameter variance with increasing parameter values and on considerations of interpretability of the resulting models.

This study included unilaterally and bilaterally injured individuals. Most of the previous studies investigating biomechanical or sensorimotor impairments included individuals with unilateral LE only (Alizadehkhayat et al., 2007a; Alizadehkhayat et al., 2007b; Alizadehkhayat et al., 2009; Bisset et al., 2006; Pienimäki et al., 1996; Pienimäki et al., 1997; Pienimäki et al., 2002; Stratford et al., 1987). In this study, the flexibility of the prespecified mixed-effects model allowed inclusion of participants with bilateral injury. In this model, bilateral differences within healthy -LE controls and within bilaterally injured +LE participants contribute to accurate estimation of the dominance effect, while both intra-participant differences in unilaterally injured +LE participants and inter-participant differences between -LE controls and +LE participants contribute to accurate estimation of the injury effect regardless of whether the LE injury is unilateral or bilateral.

Grip strength and mechanical parameters may provide different information about hand function. Measurement of grip strength involves a static exertion while measurement of mechanical properties involves a dynamic exertion in which the forearm rotates rapidly at the rate of around three times per second. It is possible that LE may affect participants' ability to grip the device, causing a reduction in mechanical parameters. Our current data does not permit us to distinguish independent effects of LE on grip strength and mechanical parameters. Future research that assesses grip strength simultaneously during measurement of mechanical parameters may help understand the effect of grip strength on mechanical parameters.

Previous research has found that short-term recovery of grip strength and mechanical parameters in healthy individuals is dissimilar. Following eccentric exercise, grip strength had recovered to baseline levels 24 hours later while mechanical parameters remained diminished (Chourasia et al., 2009; Sesto et al., 2008). It has been postulated that it might be unrealistic to expect one or two tests to detect a change in function (Alizadehkhayat et al., 2009; Schlumberger et al., 2006; Stratford et al., 1987). Interestingly, improvements in pain and grip strength have been reported following treatment for LE but deficits in reaction time persisted at 52 weeks following treatment (Bisset et al., 2009). This suggests that functional recovery may not be complete even when symptoms are resolved. While lower grip strength

and mechanical parameters were both observed due to LE, it is unknown if their long term recovery is similar. Further research is needed to understand these changes.

To the best of our knowledge this is the first study which has modeled the change in grip strength per unit change in the VAS score. In this study we observed a grip strength decrease in injured limbs of 34 N per unit change in the VAS score. Previous studies (Bisset et al., 2006; Stratford et al., 1987) have reported moderate correlations ($r = 0.44 - 0.47$) between pain-free grip strength and VAS scores, but no change in grip strength per unit change in VAS score was provided. The large amount of inter-participant variation implies that this relationship be used cautiously but it may be useful for clinicians if grip strength measurements are not possible with severely symptomatic LE patients.

Collectively, lower mechanical stiffness and damping is associated with greater upper limb displacement and discomfort (Lin et al., 2003; Sesto et al., 2008; Sesto et al., 2006). These mechanical parameters are important for function because they directly quantify the muscle and tendon dynamic capacity to counteract loads and control posture when reacting to external force perturbations. Therefore, a decline in mechanical parameters may negatively affect upper limb function. For individuals engaged in manual or repetitive activities involving the upper limb, a reduction in ability to oppose these forces may result in increased risk for injury or recurrence.

There are several limitations to the study. Except for the radiologist, other assessors were not blinded to participant status (+LE vs. -LE). To minimize assessor bias during measurement, a standard operating procedure was developed and used. The operating procedure included the experimental protocol and specific instructions to participants during data collection. In addition, the mechanical parameters extraction procedures were also standardized to minimize bias. Grip strength was not measured simultaneously during the assessment of mechanical parameters and thus, the effect of grip strength on mechanical parameters is currently unknown. Further research is needed to distinguish independent effects of injury on grip strength and mechanical parameters. In addition, while participants did not report pain during evaluation of mechanical parameters, pain or the fear of pain may also affect these parameters.

5 Conclusion

A significant effect of injury was observed on the mechanical parameters of stiffness and damping. Decreased stiffness and damping are indicative of a lower capacity to oppose rapidly rising forces and quantify an important aspect of upper limb function. These measures may assist with evaluating severity and recovery of LE, but further longitudinal studies are needed.

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Figure 1.

Boxplots of mechanical parameters and grip strength. Boxplot pairs compare distributions of the given parameter as assessed in the N=non-dominant and D=dominant limb for uninjured controls (n=10), patients with unilateral injury to dominant limb (n=12), and patients with bilateral injury (n=15). The subjects with non-dominant limb injury (n=2) are not included in these plots.

Figure 2. Coronal MR scans of (a) uninjured limb and (b) injured limb. Circled area indicates common extensor tendon (CET). +LE participants show higher signal intensity in the CET.

Table 1

Participant demographics

Characteristic	+LE	-LE
Males / Females (n)	17/12	5/5
Age (years) (Mean (SD))	48 (8.3)	42.6 (6.9)
Symptom Duration (years) (Mean (SD))	3.4 (3.5)	-
Hand Dominance (n)	Right = 27; Left = 2	Right = 8; Left = 2
Unilateral / Bilateral Symptoms (n)	14/15	-
Unilateral – Dominant Arm Symptomatic (n)	12	-
Unilateral – Non-dominant Arm Symptomatic (n)	2	-
Job Status	FT = 25; PT = 4	FT = 9; PT = 1
Full time (FT)/ Part Time (PT)/ /Not working (NW)		
Work Restrictions (Yes/No)	Yes = 12; No = 17	Yes = 0; No = 10
Participation in sports (> 1 hour per week)	Yes = 17; No = 12	Yes = 9; No = 1

Mean (SD) for mechanical parameters and grip strength. Frequency of MR scores is also indicated. MR results from the more injured limb of the bilateral LE participants are included.

Table 2

Limb Status	Controls (n=10)		Unilateral LE in Dominant Limb (n=12)		Bilateral LE (n = 15)	
	Dominant Limb	Non-dominant Limb	Dominant Limb	Non-dominant Limb	Dominant Limb	Non-dominant Limb
	Non-injured	Non-injured	Injured	Non-injured	Injured	Injured
Stiffness (Nm/rad)	14.9 (5.6)	12.1 (4.0)	12.8 (3.4)	15.7 (6.3)	14.0 (4.4)	11.7 (4.1)
Damping (Nms/rad)	0.031 (0.014)	0.023 (0.008)	0.029 (0.012)	0.030 (0.015)	0.028 (0.011)	0.021 (0.011)
Mass (kg m^2)	0.0043 (0.0008)	0.0039 (0.0011)	0.0042 (0.0015)	0.0036 (0.0011)	0.0047 (0.0012)	0.0039 (0.0015)
Grip Strength (N)	423 (119)	382 (108)	210 (110)	379 (81)	299 (144)	236 (177)
MR Scores (n)	Grade 0 = 10		Grade 0 =0; Grade 1 = 1; Grade 2 = 4; Grade 3 = 7		Grade 0 =0; Grade 1 = 5; Grade 2 = 6; Grade 3 = 3	