Local Sensation Changes and Altered Hip Muscle Function Following Severe Ankle Sprain

Background and Purpose. Changes in sensory information have been shown to influence muscle function locally. Some clinicians, however, believe that the influence may be more extensive. To investigate this clinical concept, subjects with severe ankle sprain were assessed for local sensation changes and proximal hip/buttock muscle function. Subjects. Of a total of 361 potential subjects whose medical histories were assessed, 20 men (age 18-35 years) who had previously sustained a severe unilateral ankle sprain and 11 matched "control" subjects with no previous lower-limb injury participated in the study. Methods. Using this experimental model, tests of vibration sensation in the ankle (indicating sensation changes) as well as surface electromyography of muscle recruitment patterns for hip extension (indicating muscle function proximally) of the biceps femoris, gluteus maximus, and lumbar erector spinae muscles were made on both sides of the unilaterally injured and matched control subjects. Results. Significant decreases in vibration perception and significant delays in gluteus maximus muscle recruitment during hip extension were found in the injured group. Conclusion and Discussion. The author concludes that both local sensory and proximal muscle function changes are associated with unilateral severe ankle sprain. [Bullock-Saxton JE, Local sensation changes and altered hip muscle function following severe ankle sprain. Phys Ther. 1994;74:17-31.]

Key Words: Ankle, Electromyography, Hip, Muscle performance, lower extremity, Sensation, Sprains and strains.

The existence of a complicated feedback system between muscles and joints and the central nervous system is well recognized. Interference with sensory feedback may affect a person's ability to monitor movements or to make appropriate adaptations and adjustments to movement. For example, a change in postural stability when a person stands on one leg following ankle sprain was attributed by Freeman1 to altered proprioceptive input from the ankle joint and its influence on the postural control of the muscles.

This relationship between joint receptor information and muscle function has interested researchers for some years, and the relationships between stimulation of joint afferents and muscle activity have been demonstrated in both animal and human studies.2-5 For example, Ekholm et al2 investigated the response to various articular stimuli of decerebrate and, in some instances, spinalized cats. They found that increasing the articular pressure in the knee joint, as well as pinching its capsule, led to decreased quadriceps femoris muscle (ie, extensor) activity, whereas pinching the knee capsule elicited an increased response from the knee flexors (biceps femoris muscles). In their study of human subjects, Stokes and Young3 considered that joint injury can decrease the activity of muscles, leading to weakness and wasting. They measured the rectified integrated electromyographic (EMG) activity of both quadriceps femoris muscles of patients who had a meniscectomy or an arthrotomy and...
This experimental evidence supports the clinical observation that a joint injury involving sensory receptors can influence the muscle function about that joint. However, a more complex relationship than this has also been proposed. This proposed relationship is that altered sensation in one joint could lead to muscle function changes in another more proximal joint. This concept has been the basis of teaching by Lewitt and Janda for several decades. Some experimental data on cats do exist demonstrating that the motor system has a tendency to extend dysfunction into a larger area.

Although difficult to extrapolate results from animal studies to human behavior, Wyke observed that in the cat, an injury of the joint capsule or ligaments influences muscle activity not only in muscles that cross the injured joint, but also in remote muscles. Wyke stated that...

Thus, the arthrogenic reflex might be considered as a triggering factor that would initiate a whole chain of adaptation reactions, eventually resulting in a changed movement pattern. The possibility that sensory deficits associated with localized injury in one part of the body influence muscle function in another and may ultimately lead to pain has considerable implications for the physical therapist, influencing both the preventive and therapeutic approaches to patient care.

Wyke also argued that articular sensory information is vital to normal postural reflexes. He cited observations of impaired postural reflex activity of muscles following severe ankle sprain of humans and proposed that this might be a reflection of the impaired proprioceptive information from the damaged mechanoreceptors. As afferent impulses travel to cerebellar and cortical centers, the impaired afferent information from the ankle joint may be sufficient to impair the motor regulation of body posture. In their experimental study of postural stability following ankle sprain, Tropp et al. found a significant decrease in postural stability when compared with uninjured subjects, thus confirming Wyke's observations. Recent experiments by Gauffin and colleagues have indicated that patients with unilateral anterior cruciate ligament injury demonstrated bilateral alterations in their postural control when compared with uninjured subjects. They postulated that these alterations may be due to "central adjustments of motor control." The postulation that changes in sensory input could cause alterations in the function of muscles in a joint remote from the injury seems to be well justified, although no direct experimental evidence of this in humans has yet been reported.

This study was conducted, therefore, to investigate whether a localized lesion at a peripheral joint such as the ankle influenced the sensation in that area as well as the muscle function in more proximal regions such as the hip and pelvis and, if so, whether such changes were interrelated. The sensory and muscle function in both limbs of subjects who had previously sustained a severe unilateral ankle sprain was compared with that in both limbs of uninjured ("control") subjects.

For this study, appropriate tests of sensory and muscle function needed to be selected. Freeman et al. theorized that ankle instability following injury develops primarily due to lesions of mechanoreceptors in the joint capsule and ligaments. This instability impairs both the static position and joint movement sense. This theory was not supported by Gross, who compared active and passive joint position sense in both injured and uninjured subjects and found no significant difference between them. However, the method of testing used for assessing joint position sense involved strapping the foot to a movable footplate with firm pressure. It is possible that mechanoreceptors on both plantar and dorsal surfaces of

recorded large decreases (80%) in quadriceps femoris muscle activity on the side of surgery. This effect persisted for up to 15 days postoperatively (30%-40%), despite the lack of pain at that time.

A possible mechanism for this decreased activity might be the excitation of joint afferents in the capsule because of pressure caused by joint infusion. Indeed, in 1965, De Andrade et al. showed that in healthy human subjects and in those with pathology, infusion of saline into the knee joint was responsible for decreased activity of the quadriceps femoris muscles. Results of recent studies by Iles et al. have indicated that as the volume of saline infused into the human knee joint is increased, the amplitude of the H-reflex is decreased and that even apparently imperceptible volumes of saline could decrease quadriceps femoris muscle activity. In these studies, the decrease of extensor activity following afferent stimulation was highlighted.

The relationship between ankle articular mechanoreceptor function and the reflex activity in the limb of the cat was also investigated by Freeman and Wyke. Establishing the normal reflex muscular response of the tibialis anterior and gastrocnemius muscles, these researchers decreased the afferent information from the joint by local anesthesia and by electrocoagulation of the articular tissues. Both procedures caused an abolition of the normal reflex muscular response to movement, indicating the importance of articular information to regulation of muscle activity. Freeman and Wyke believe that muscle activity is regulated through the contribution of the articular impulses to a facilitatory bias to the gamma motoneurons of the muscle spindles. If such an influence exists, then their early assertion that articular afferents influence local muscle activity is correct and has been supported by the later research of Iles et al.

This experimental evidence supports the clinical observation that a joint injury involving sensory receptors can
the foot, which were not compromised by the lateral ligament ankle injury, were able to provide sufficient cues for the subject to determine ankle joint position. Barrack and colleagues\(^5\) appear to have developed a successful measurement procedure for eliminating pressure cues during testing of joint position sense of the knee following anterior cruciate ligament injury. These researchers found significant deficits in joint position sense of the knee.

If damage to sensory receptors from severe ankle joint sprain is to be accurately measured, a test that is sensitive to changes in sensory receptor function is needed. Two factors were considered in this regard: (1) the influence of joint stress on discharge rates of mechanoreceptors and (2) the effects of age on sensation. Wyke,\(^9\) in his description of three types of articular nerves, outlined how the frequently occurring group II nerve fibers terminated onto both low-threshold, slowly adapting mechanoreceptors (type I) and low-threshold, rapidly adapting mechanoreceptors (type II). The type I mechanoreceptors, found in clusters around the joint capsule, where the greatest degrees of stress during movement are likely to occur, are sensitive to changes in joint pressure and position. Their rate of discharge adapts rapidly to the degree of joint stress. It is likely that capsular tears, rupture of small nerve fibers, and joint edema following ankle sprain could cause alterations of discharge from these receptors, as indicated by Freeman et al.\(^\text{13}\)

In persons without joint injuries, perception of some superficial and deep sensations decreases with age. These sensations include tactile, two-point discrimination; vibration perception; and joint movement sense.\(^13\) Such an age-related decline suggests that these sensory modalities are vulnerable to change. Vibration perception requires information from both superficial and deep mechanoreceptors as well as a functional cortical sensory association area.\(^16\) Testing vibration perception, therefore, would provide information on the integrity of sensory receptors possibly damaged due to ankle ligamentous injury. This assessment of sensation is capable of a high degree of control in comparison with current tests used for assessing tactile, two-point discrimination or joint movement sense around the ankle. For these reasons, vibration perception was chosen as the variable for assessment of sensory function in this study.

Muscle function in each limb was investigated in terms of the temporal sequence of activation (as illustrated in EMG signals) of the gluteus maximus, hamstring, and ipsilateral and contralateral lumbar erector spinae muscles during the movement of hip extension from a prone-lying position. Janda\(^17\) has claimed that the determination of the order of activation of muscles performing a simple movement is important for the understanding of the methods used by patients to move their body and that this knowledge helps to reveal the area of impairment. Hip extension was selected for this study, not only because the studied muscles were separated from the site of injury but also because of its functional importance in stance and locomotion. Due to the complexities of the gait process, it was considered advisable to isolate the hip extension motion rather than to study muscle function during gait. Much greater control could be imposed experimentally by assessing muscle activation during hip extension from a prone-lying position than would be possible during locomotion.

In my study, the effects of ankle sprain (the independent variable) on vibration perception at the ankle and the pattern of activation of specified muscles around the hip and low back (the dependant variables) were measured. A matched control group was used for comparison. Only subjects who had sustained a unilateral ankle sprain were included in the injured group, so that side-to-side differences between their injured and uninjured sides could be compared with the normal side-to-side differences demonstrated in the uninjured control group.

**Method and Materials**

**Subjects**

Two groups of subjects were studied: an "injured" group, who had previously sustained a severe unilateral ankle sprain, and a matched "control" group, who had no previous lower-limb injury. To control variables between the two groups of subjects, a suitable population of sufficient size was sought. The armed forces provided such a source. The Australian Defence Force (Army) gave permission for their soldiers and officers to volunteer to be subjects for this study.

For the injured group, subjects were included if they had previously sustained a grade II+ or III (severe or unstable\(^\text{19}\)) lateral ankle sprain that was significant enough to have caused marked swelling at the time of injury and discomfort while walking. Treatment must have included a period of immobilization. The subjects' right side must also have been the preferred (or "skill") side. Subjects were excluded if they had had a significant injury to any other lower-limb joint or a significant injury to either leg. Of particular concern was the need to exclude subjects who may have had a history of incoordination or clumsiness (operationally defined as a history of sensory and/or motor dysfunction related to injury, in the absence of intellectual impairment). It was essential to ensure that an existing neurological deficit was not a predisposing cause of the ankle sprain, because the finding of differences in localized sensory function in the control group could then be said to be a cause, rather than an aftereffect, of the injury.

I assessed the medical histories of 361 potential subjects; 80 subjects (22%) were found to have sustained an ankle sprain on both sides, and 233 subjects (65%) either had injuries in other joints or were unavailable to participate in the study. Sixty-four men (18%) underwent the detailed
Variables measured were age, physical characteristics such as height and weight, and level of physical activity (eg, during sports and work). Subjects for the control group, who matched subjects in the injured group in these characteristics, were sought from the same army units. Eleven men fitting the criteria were found. Table 1 illustrates the distribution of relevant variables between the two groups.

**Measurements**

**Vibration perception.** Dyck et al have discussed the problems associated with the measurement of the threshold of vibration perception and the inadequacy of current clinical methods (such as the use of tuning forks) in providing reliable, repeatable results. For my measurements of vibration sensitivity, it was desirable to ensure that frequency and amplitude of vibration could be varied, a consistent pressure of application could be maintained, and the subject could remain alert and cooperative. To meet the first of these criteria, a mechanical oscillator connected to a Power oscillator was used. This instrument allowed variation of both frequency and voltage and provided measures of output voltage directly related to acceleration (force intensity) of the oscillator head at each of the chosen frequencies. To ensure a constant pressure of this device on the skin, the oscillator was suspended from one end of a system of pulleys and a mass of equal weight was suspended from the other end as a counterbalance.

The subject was positioned side lying with the leg to be tested uppermost and secured in a lower-leg rigid support (back slab) to control the degree of ankle dorsiflexion, and supported on a high-density foam cushion (Fig. 1). The oscillator was positioned perpendicular to and just touching a point on the inferior fibular head, and the weight on the counterbalance was reduced by 50 g. The head of the oscillator, therefore, made contact with the fibular head with a gravity-applied force of 50 g. The head of the oscillator, therefore, made contact with the fibular head with a gravity-applied force of 50 g. The voltmeter, which reflected the amplitude of oscillation of the vibrator, indicated both when vibration was occurring and when it had ceased.

Because there appears to have been little research into the perception of vibration at different frequencies, a range of frequencies (ie, 100, 150,
200, and 250 Hz) was assessed. For each frequency, the oscillator amplitude (which could be termed "vibration strength") was slowly increased until the subject stated that he perceived vibration. This voltage was recorded as the threshold. Two measurements at each frequency were taken on one limb to provide an estimate of measurement error, before commencing the series on the second limb. The order of presentation of the series of frequencies to each subject and between subject sides was randomized. One researcher (JEB-S) tested all subjects.

To determine the consistency of subject threshold to vibration perception, a repeatability test was carried out prior to the major study. Ten repetitions at each frequency on one limb were chosen randomly from a subset of the sample composed of five injured group subjects and five control group subjects. The repetitions of each frequency were taken within a 1-hour time span with a 30-second interval between repetitions. The confidence interval limits of the means (mean±×standard error) and their standard deviations of the "within-subject-between-replication" variation (derived from a suitable analysis of variance) for each frequency were comparable for each group and are listed in Table 2. These results indicated that for uninjured subjects and for those with previous ankle injury, the threshold of vibration perception at each frequency was repeatable on the one day.

**Table 2.** Confidence Interval and Standard Deviation for Repeatability Test of Vibration Perception (in Meters per Square Second) (n=10)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
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<tbody>
<tr>
<td>Frequency (Hz)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>C</td>
<td>I</td>
<td>C</td>
<td>I</td>
</tr>
<tr>
<td>CI (±SE)</td>
<td>0.41±0.52</td>
<td>0.78±0.11</td>
<td>0.29±0.07</td>
<td>1.93±0.33</td>
</tr>
<tr>
<td>SD</td>
<td>0.19</td>
<td>0.33</td>
<td>0.27</td>
<td>1.26</td>
</tr>
</tbody>
</table>

\*p<0.05.
\*C=control group (n=5).
\*t=injured group (n=5).

Muscle activation. Surface EMG was used to provide information regarding the activation of the specified muscles during hip extension, utilizing bipolar surface electrodes (silver-silver chloride) on each of the ipsilateral and contralateral lumbar erector spinae, gluteus maximus, and hamstring muscles of both limbs. With subjects positioned prone lying, EMG sites were identified, and electrodes were placed 10 mm (0.39 in) apart on each prepared site. The electrodes were positioned parallel to the line of the muscle bellies and over the area of greatest muscle bulk, determined after a resisted contraction of the specific muscle. Lumbar erector spinae muscles were monitored adjacent to the intervertebral level of L2-3, the upper fibers of the gluteus maximus muscle were monitored, and electrodes were placed on the hamstring muscles over the biceps femoris muscle. For each hip extension motion, signals from the four muscle groups were preamplified using a
Medelec PA65 preamplifier\(^1\) before passing to a Medelec AAM63 amplifier/filter.\(^4\) The signals were sampled at a rate of 2,500 Hz, were bandpass filtered at a lower frequency of 0.8 Hz and a higher frequency of 800 Hz, and were recorded on an eight-channel ink jet chart recorder\(^5\) for monitoring of the signal during data collection. The EMG signals were also passed to an analogue-to-digital converter in a computer and stored for analysis.

The starting position of each leg was traced onto a sheet of paper placed over the base of the test bed to ensure a consistency of position. A feedback system was devised to assist the subject in controlling his own range of motion. An inclinometer\(^6\) provided a recording of the motion of the limb during hip extension. The inclinometer was connected to an oscilloscope positioned below a face hole in the test bed to be monitored by the subject. The inclinometer produced an output in the form of a moving line on the oscilloscope, and an initial zero "base" line (representing the limb in neutral) and a "target" line (representing the designated 15° range of hip extension) were marked. Thus, the subject had feedback for the position of his limb as he moved the limb through the range of motion.

The inclinometer, fixed to a curved metal plate, was strapped to the lateral side of the thigh on a line between the greater trochanter and the lateral femoral condyle with the femur in a horizontal position, so leading to zero output of the inclinometer (giving the base line). Passive limb movement to the edge of a 15-degree template allowed the 15-degree target line trace to be recorded on the oscilloscope. When the subject moved his limb, a third (moving) line provided feedback of the limb's position in relation to the target line. By connecting the inclinometer to the chart recorder and computer, the position of the limb was recorded at rest and during movement.

Speed of motion was controlled by the subject moving the limb through the 15-degree range of motion at a rate equal to three beats of a metronome set at 72 beats per minute. That is, the limb moved through a 6-degree arc of motion per second, which was considered to be approximately equal to a slow walking speed.

Subjects were encouraged to relax prior to the hip extension, the chart recording indicating whether the muscles were at rest. Only then was the trial commenced, with EMG signals being recorded for a count of three beats of the metronome prior to the request to extend the hip. This initial "at rest" recording not only provided a base line signal prior to hip extension, but also allowed the EMG recording of any activity within the muscle as the subject prepared to move into hip extension. An initial training period ensured that the subject understood what was required of him. For each subject, a 10-second recording of EMG and inclinometer signals was made during each of the six tests on each side. A 10-minute interval separated the tests on the two sides to allow recovery from any possible fatigue. The same researcher carried out all testing.

For analysis of EMG data, the order of muscle activation represents the sequence of each muscle's entry into a coordinated muscle activity. Visual observation is the method usually used by researchers for this determination. For this study, however, it was important for statistical purposes to find a quantitative measure that would allow comparison between groups of subjects of the relative behavior of muscles contributing to a group activity.

Because one or more muscles might contract prior to the commencement of hip extension and the starting point of individual muscle contractions relative to hip motion might vary, a consistent reference point for comparison purposes was needed. Therefore, the commencement of hip movement (H) was taken as a reference. The temporal measure used to recognize this was the time span (in seconds) between onset of individual muscle activity (O) and commencement of hip movement (H), as determined by the inclinometer (ie, O-H).

Calculation of the time span between points of onset of the first and fourth muscles provided a second quantitative measure in relation to muscle activation, allowing a determination of whether injury influenced the time taken for activation of all four muscles. The second temporal measure used, therefore, was the time span (in seconds) for the sequence of activation of the first (M\(_1\)) and fourth (M\(_4\)) muscles (O, M\(_1\)-M\(_4\)). The incorporation of a time reference into the sampling procedure and the computer acquisition of EMG and limb-position data allowed for a determination of these temporal measures.

The EMG signals collected from the four monitored muscles during hip extension were submitted to computer analysis to determine these measures for each of the two limbs during the six trials for each subject. A special-purpose computer program (language C) was written, in which the 2,500 samples of data per second for each muscle for the 10-second recording period could be analyzed. Data used for this program related to the raw EMG signals, the EMG gain used to acquire data, the period for which the data were recorded, the number of channels used, and the data rate. The number of data points was calculated and then read in binary format. The data were stored after multiplication by 100 to enable the program to use integer arithmetic.

\(^1\)Medelec Ltd, Old Working Rd, Surrey, United Kingdom.
\(^2\)Simens AG Minograph Chart Recorder, ZW22, Postgach 101212, D-8000, Muchen 1, Federal Republic of Germany.
\(^3\)Schaezitz (A11-0001) Accelerometer, Applied Measurement, Baltec Systems, 26 Mayneview St, Milto, 4064, Brisbane, Queensland, Australia.
Table 3. Confidence Intervals and Standard Deviations for Repeatability Test of Muscle Activation Relative to Hip Extension (in Seconds) (n=10)

<table>
<thead>
<tr>
<th>Control Group (n=5)</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Muscle Group</td>
<td>Left Lumber Erector Spinae</td>
<td>Right Lumber Erector Spinae</td>
<td>Gluteus Maximus</td>
<td>Hamstring</td>
<td></td>
</tr>
<tr>
<td>Statistic</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>CI (X±SE)*</td>
<td>-0.529±0.082</td>
<td>-0.449±0.056</td>
<td>-0.504±0.090</td>
<td>-0.464±0.060</td>
<td>-0.461±0.069</td>
</tr>
<tr>
<td>SD</td>
<td>0.326</td>
<td>0.232</td>
<td>0.356</td>
<td>0.245</td>
<td>0.272</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injured Group (n=5)</th>
<th></th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle Group</td>
<td>Left Lumber Erector Spinae</td>
<td>Right Lumber Erector Spinae</td>
<td>Gluteus Maximus</td>
<td>Hamstring</td>
<td></td>
</tr>
<tr>
<td>Statistic</td>
<td>Uninjured</td>
<td>Injured</td>
<td>Uninjured</td>
<td>Injured</td>
<td>Uninjured</td>
</tr>
<tr>
<td>CI (X±SE)*</td>
<td>-0.486±0.031</td>
<td>-0.432±0.037</td>
<td>-0.440±0.035</td>
<td>-0.463±0.043</td>
<td>-0.105±0.074</td>
</tr>
<tr>
<td>SD</td>
<td>0.174</td>
<td>0.200</td>
<td>0.196</td>
<td>0.231</td>
<td>0.411</td>
</tr>
</tbody>
</table>

*156, M0=2.0.
*119, M0=1.96.

where possible in the analysis. The mean of the first 500 points was calculated and subtracted from the raw data to enable the data to be centered on zero. The data were then rectified about this mean value and smoothed (four passes, 100-point bandwidth) to remove the high-frequency components of the bursts yet still leave the main burst shape. The filtering process was carried out by using a filter subroutine that used a rectangular filter (the data were linearly averaged over the bandwidth of the filter) and that allowed multiple passes over the data.

The mean of the first 500 points was again calculated and subtracted from the data to ensure that the mean value of the initial region was zero. The location of the peak data point was identified, and from this data point, the times at which the signal reached specified percentages of maximum could be determined. For the purposes of this analysis, 5% of the maximum (peak value) EMG signal was regarded as the onset of muscle activity. A second computer program was used to rank the order in which each of the four muscles was activated in each case. From this, the O, M1-M4 calculation was made. It also provided the incidence of each muscle occurring in each ranked position.

As a preliminary investigation of onset times, prior to adopting the use of the computer analysis, an independent "blind" visual observation of the EMG signals on an IBM-compatible personal computer screen for a random selection of subjects, trials, and muscles was performed to compare the accuracy of the computer analysis with human inspection. For the gluteus maximus and hamstring muscles, the computer analysis was found to give comparable results to those obtained through manual inspection of the computer-displayed signal, suitably magnified. Onset data for the lumbar erector spinae muscles were scrutinized visually to determine those trials in which the proximity of the heart beat signal to the signal of muscle activity made computer discrimination of the onset of muscle activity impossible. In such cases, the onset data were removed from the data set. Of the 372 possible values for muscle onset in the entire sample, 24 values were rejected for this reason, as reflected in the n values presented in Tables 3 and 4.

To determine the repeatability of the time of onset relative to hip motion, a study was carried out using the analysis of six movement repetitions for each subject. An analysis of variance was applied to determine the mean confidence interval and its standard deviation and the "within-subject-between-replication" variability for each of the four muscles. Results demonstrated an acceptable level of repeatability of the measurement (Tab. 3).

Data Analysis

Data acquired for muscle activation during hip extension and for vibration perception for both limbs were analyzed to investigate any differences between the injured and control groups in muscle or sensory function in each limb. The general linear model (GLM) of analysis of variance for unequal numbers was selected as the most appropriate form of analysis for these data. This model is used to reveal the influence of any indepen-
Table 4. Side-to-Side Comparisons of "Threshold" Vibration Perception (in Meters per Square Second)*

<table>
<thead>
<tr>
<th>Control Group (n=11)</th>
<th>Frequecy (Hz)</th>
<th>Mean of Left Side (L)</th>
<th>Mean of Right Side (R)</th>
<th>Mean Difference L-R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>0.395</td>
<td>0.399</td>
<td>-0.004*</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>0.299</td>
<td>0.317</td>
<td>-0.018*</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>1.051</td>
<td>0.495</td>
<td>0.556*</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>1.664</td>
<td>0.978</td>
<td>0.686*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Injured Group (n=20)</th>
<th>Frequency (Hz)</th>
<th>Mean of Injured Side (I)</th>
<th>Mean of Uninjured Side (U)</th>
<th>Mean Difference I-U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>0.867</td>
<td>0.824</td>
<td>0.043</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>1.400</td>
<td>0.918</td>
<td>0.482*</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>2.243</td>
<td>1.273</td>
<td>0.970*</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>3.924</td>
<td>2.324</td>
<td>1.600*</td>
</tr>
</tbody>
</table>

*Two repetitions for each side.

*Not significantly different.

*Significantly different at P<.001.

Initially, to determine any group differences in vibration perception, comparisons of the vibration strength required for subject perception at each frequency were made between the injured and control groups by consolidating the data for the two limbs in each case. Accordingly, "group" was included as an independent variable in the GLM analysis. Similar comparisons were made between groups for each of the two EMG measures. These analyses of the data do not reveal whether differences exist in one side or the other, or in both, but only that overall some alterations in vibration perception or in muscle activation may be associated with injury.

Secondly, to determine whether vibration perception or muscle activation in the injured or uninjured limb was significantly different from that on either side of the control group subjects, further analyses were undertaken comparing the side-to-side differences between groups.

**Results**

**Vibration Perception**

Analysis of data for vibration perception at each frequency demonstrated a significant difference between the injured and control groups (P<.001). As Figure 2 demonstrates, vibration strength needed to be greater for the injured group than for the control group in order for the subjects to perceive the stimulus.

A comparison of side-to-side differences between groups (uninjured versus injured) showed that whereas there were significant differences between left and right sides at only one of the four frequencies (200 Hz) for the control group, there were significant differences between injured and uninjured sides at three of the frequencies (150, 200, and 250 Hz) for the injured group (Tab. 4).

Comparison of the mean values for each side of the injured group subjects with those of each side of the control group subjects showed that a greater strength of vibration was necessary to reach threshold perception on both the injured and uninjured sides of the injured group subjects than on either the left or right side of the control group subjects. To determine whether the threshold perception values for the uninjured side of the injured group subjects contributed to these group differences, Student's t-tests were applied to the uninjured side of the injured group subjects versus each side of the control group subjects. Significant differences were found to exist at all frequencies (P<.05) (Tab. 5).

**Electromyographic Analysis**

Separate statistical analyses were performed on data for each temporal variable (ie, O-H; O, M1-M4). To determine whether there were significant differences between the injured and control groups, a GLM analysis was performed.

**O-H.** Reflecting the preparatory activation of the muscles prior to the limb motion in hip extension, the onset times for each of the four muscles in almost all instances preceded the time of commencement of the reference activity (ie, hip motion), giving a negative value for O-H. The greater the negative time span, the earlier the onset of activity of that muscle prior to hip extension motion, whereas the smaller the negative time span, the later the onset. The results of analyses of this variable need to be interpreted with this in mind. Figure 3 represents typical EMG recordings of a control group subject and an injured group subject.
The analysis of side-to-side differences for the gluteus maximus and hamstring muscles revealed that for the control group, the time span (O-H) was significantly greater on the left (stance) side than on the right (preferred or skill) side (P<.05), indicating an earlier onset of gluteus maximus and hamstring muscle activity on the left side for uninjured subjects (Tab. 6). The side-to-side differences (injured versus uninjured sides) in the injured group did not reach significance for either of these muscle groups. The significantly later time of onset of gluteus maximus muscle activity for the injured group compared with that of the control group (ie, with data for two sides consolidated), however, suggested a delay in gluteus maximus muscle activation on both sides of the injured group subjects. Examination of the data in Table 6 demonstrates that this was so. A Student's t test applied to the gluteus maximus muscle activity onset data for the uninjured side of the injured group versus each side of the control group (ie, with data for two sides consolidated), however, suggested a delay in gluteus maximus muscle activation on both sides of the injured group subjects. Examination of the data in Table 6 demonstrates that this was so. A Student's t test applied to the gluteus maximus muscle activity onset data for the uninjured side of the injured group versus each side of the control group highlighted the significant difference that existed (P<.0005). No significant side-to-side differences were found to exist for either the left or right lumbar erector spinae muscles.

\( O, M^1-M^4 \). Analyses of the consolidated data relating to the time span between the onset of activity of the

![Figure 2. Vibration perception threshold of injured versus control group subjects. Note that the greater the strength of vibration, the poorer the subjects' perception of vibration.](image)
level and the timing of onset of gluteus maximus muscle activity relative to hip extension (O-H). Results demonstrated that a positive correlation existed for the injured group between threshold vibration perception and gluteus maximus muscle activation for the 250-Hz frequency ($P<.05$). That is, the less sensitive the subjects were to vibration at 250 Hz, the longer the delay in recruitment of the gluteus maximus muscle for hip extension.

**Discussion**

Significant differences in the sensory and muscle function of subjects with severe ankle sprain were shown to exist when compared with that of uninjured subjects. The decreased ability to perceive vibration appears to confirm the views of Freeman and Wyke that a ligamentous/capsular injury influences the integrity of local sensory receptors on the side of injury, presumably through direct damage.

The significant delay in activation of the gluteus maximus muscle in the injured group subjects and the positive correlation between a poorer perception of vibration at 250 Hz and gluteal muscle delay suggests that joint injury involving sensory receptors could influence the function of muscles proximal to and removed from the injury side. Even though this study could not determine cause and effect, this association provides support for the idea of a reflex chain of events that occurs following injury, as proposed by Lewit and Janda.

The normal activation behavior of the hamstring and lumbar erector spinae muscles in the injured group can be viewed together with the delay in activation of gluteus maximus muscle. A change in activation of all muscles could have led to the assertion that all subjects in the injured group had a motor regulation problem, as has been intimated by previous studies. The finding of significant activation changes in the gluteus maximus muscle, however, only points to the possibility that such a change is associated with the ankle injury. Be-

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**Figure 3.** Graphic illustration of an electromyographic recording of a typical recruitment pattern of (a) a control group subject and (b) an injured group subject. (Arrows indicate onset of activation; numbers indicate the sequence of activation.)

First and fourth muscles (O, M1-M4) to be recruited revealed a highly significant difference ($P<.001$) between the injured and control groups. As Table 7 demonstrates, although the mean time span for the control group was 0.306 second, it was 0.527 second for the injured group, or 72% longer than for the control group.

The GLM analysis showed that there was no significant difference between sides in the O, M1-M4 time span for either group. Examination of the ranking incidence indicated that the gluteus maximus muscle was almost always the fourth muscle to be activated. This delayed activation was therefore responsible for the greater O, M1-M4 time span found in the injured group.

The delayed activation in the gluteus maximus muscle was used as the variable for a correlation analysis of muscle and sensory function. A Pearson Product-Moment Correlation Coefficient analysis was applied to data for both groups relating to vibration strength at threshold perception level and the timing of onset of gluteus maximus muscle activity relative to hip extension (O-H). Results demonstrated that a positive correlation existed for the injured group between threshold vibration perception and gluteus maximus muscle activation for the 250-Hz frequency ($P<.05$). That is, the less sensitive the subjects were to vibration at 250 Hz, the longer the delay in recruitment of the gluteus maximus muscle for hip extension.

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Table 6. Comparison of Time Spans Between Onset of Muscle Activity and Commencement of Hip Movement for Groups (in Seconds)

| Muscle Group                | Control Group (n=11) | Injured Group (n=20) | Difference
|-----------------------------|----------------------|----------------------|--------------
|                             | Side                 |                      | L-R          |
| Gluteus maximus             | Side                 |                      |              |
| Left (L)                    | -0.451               |                      | -0.202a      |
| Right (R)                   | -0.249               |                      |              |
| Difference                  |                      |                      |              |
| Left (L)                    | -0.530               |                      |              |
| Right (R)                   | -0.450               |                      | 0.080b       |
| Right lumbar erector spinae |                      |                      |              |
| Left lumbar erector spinae  |                      |                      |              |
| Gluteus maximus             |                      |                      |              |
| Hamstring                   |                      |                      |              |
| Left lumbar erector spinae  |                      |                      |              |
| Right lumbar erector spinae |                      |                      |              |

*P<.05.

NS=not significant.

cause cause and effect were not the focus of this study, further research is warranted to help clarify these interrelationships.

Differences in vibration perception and activation of the gluteus maximus muscle on the uninjured side as well as the injured side of the injured group subjects when compared with the control group subjects support the concept of central adjustment of motor control following injury. This finding suggests that a reflex chain of events is not limited to the side of injury, but that there could also be implications for influences on the uninjured side.

These results suggest that as a result of injury to the ankle joint, the activity of the hip extensors on both sides of the body is diminished. Whereas Stokes and Young and Iles et al have demonstrated decreased extensor activity at the site of injury, the results of this study suggest that there could be a direct relationship of decreased activity of the extensors of the lower limb, involving muscles not only remote from the site of injury but also on the opposite side of the body. It is also possible that even after pain following the ankle injury had ceased, the function of the gluteus maximus muscle in extending the hip was compromised due, perhaps, to an alteration in gait pattern established during the period of injury. Such possibilities are the subject of further research.

Table 7. Comparison of Mean Time Span Between Onset of Activity of First and Fourth Muscles

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>( \bar{x} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (n=11)</td>
<td>120</td>
<td>0.306*</td>
</tr>
<tr>
<td>Injured (n=20)</td>
<td>229</td>
<td>0.527*</td>
</tr>
</tbody>
</table>

*If of error in ANOVA=6.73, P < .001.

This study has a number of implications for the physical therapist. In view of the likelihood that a deficit in sensory function is associated with decreased muscle activity around other joints, a rehabilitation program should include a focus on improving sensory function. Because muscles respond in different ways to peripheral injury, the results of this study suggest that the effects need to be sought in areas remote from the site of injury. This study has examined only some of the muscles around the hip. Further investigations could reveal whether muscle function changes also occur in other joints following ankle injury (eg, in the knee or vertebral joints), or indeed, whether they might occur as a result of the effects of gluteal muscle delay.

The differences in sensory function and in the function of some muscles on the uninjured side are also important in treatment. Whether such differences are due to dysregulation at the cortical level or at a spinal level has still to be determined. Nevertheless, the existence of differences highlights the need to examine both sides of the body in assessment. These results emphasize the importance of the physical therapist paying attention to motor control and to the function of muscles around joints separated from the site of injury.
Conclusion

The results of this study have shown that both local sensory and proximal muscle function changes are associated with unilateral severe ankle sprain and that when some aspects of sensory and motor function deficits are considered, there is a positive correlation between the two. If comprehensive and effective management of injury is to be ensured, a holistic approach to assessment is essential.

References


Invited Commentary

Dr Bullock-Saxton's article examines theoretical concepts of neural adaptation and motor control changes following soft tissue injury. Equally as important, the author poses the clinical question, Should motor planning/learning rehabilitation be an integral part of treatment protocols following orthopedic-type injuries? These issues are ripe for investigation, and, as a neuroscientist and a physical therapist, I was very pleased to be invited to provide this commentary.

First and foremost, I would like to commend the author for tackling a technically, and theoretically difficult, problem. The hypothesis that changes within articular sensory receptors—as a result of soft tissue injury—alter postural reflexes, has a strong theoretical rationale. The Bobaths and Signe Brunnstrom were among the first to make clinical use of the importance of sensory input to motor control. Scientists, such as Goldberger, Huiller, and Pearson, have shown the importance of afferent information to motor control. Similar to Dr Bullock-Saxton's findings in the lower extremity, Smith and Brunolli have reported proprioceptive deficits in the upper extremity following soft tissue disruption. In my laboratory, we have collected preliminary data indicating change in muscle afferent activity can actually alter neural responses to muscle fatigue. The possibility that sensory changes in one joint may cause alterations at sites distant to it is also consistent with recent computational models of human movement. The nervous system appears to control movement by comparing degrees of freedom at each joint. If joint A moves x degrees, then other joints will alter their movement trajectories accordingly in order to attain the desired end point of movement. Presumably, this is why our handwriting has the same stylistic appearance, regardless whether we write it billboard or microchip size.

The author of this report has taken on a complex task. It should not be surprising, therefore, that certain vulnerabilities exist regarding methodology and data interpretation. Because questions regarding methodology tend to be of interest mainly to other investigators, I will only briefly mention a few concerns. I would have found it useful to know the average amount of time, and ranges, that had elapsed between subjects' ankle sprain and testing. Given time, some injured peripheral sensory fibers will regenerate. Relating time course of recovery to vibratory sensory perception to vibration would have been a correlation of interest. The type of physical therapy intervention and the length of time each subject was immobilized following ankle sprain would also