Assessment of Static Steadiness and Dynamic Stability at Various Stages of Healing a Grade 2 Medial Collateral Ligament Tear

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Abstract: Injuries to the ligaments of the knee are extremely common among athletes who participate in high-risk sports, or any sport that requires frequent cutting motions, jumping, or contact. In order to determine the best way to heal these injuries, it is important to understand not just the pathology of the injury, but also the biomechanical factors that are affected, including stability and steadiness. While many studies have been done to examine the stability of healthy knees, there is little to no existing literature on stability of knees afflicted by injury. In order to surpass this obstacle, static steadiness and dynamic stability data was collected using the Lockhart Monitor phone application and Xsens accelerometers, respectively, both before and after completion of a course of physical therapy in a patient with a grade 2 medial collateral ligament (MCL) tear. These results were then used to determine the degree to which the prescribed physical therapy protocol was effective in healing the MCL, which can be useful for tweaking the individual protocol for future conservative treatment and management of the injury.

Keywords: biomechanics; dynamic stability; inertial measurement unit; MCL tear; static stability

1. Introduction

The medial collateral ligament (MCL) is one of the most commonly injured structures of the knee, especially by athletes who participate in sports with copious amounts of valgus knee loading [1]. Fortunately, most people who sustain an injury to the MCL can achieve pre-injury activity levels with nonsurgical treatment; however, it is not uncommon for other structures to be damaged in addition to the MCL as a result of traumatic injury to the knee. If the injury is isolated to the MCL, the most common forms of conservative treatment include stabilization and rehabilitation, and if instability persists, then surgical reconstruction may be required [2].

1.1. Anatomy

The anatomy of the knee is relatively complex and is made up of many soft tissue and bony structures located in the joint space between the femur and tibia. The four most commonly known ligaments include the anterior cruciate ligament (ACL), medial collateral ligament (MCL), lateral collateral ligament (LCL), and the posterior cruciate ligament (PCL). The ACL and PCL cross from the back of the knee to the front, and vice versa; the MCL and LCL stabilize the knee on both of its sides. In addition to these stabilizing ligaments, there are two cartilaginous structures that act as shock absorbers for axial stresses between the femur and tibia: the medial and lateral menisci [3]. The primary biomechanical function of the medial structures of the knee is to provide stability against...
valgus stress as well as both internal and external rotation. The superficial MCL acts as the primary stabilizer to valgus stress and the deep MCL acts as the secondary stabilizer [2].

1.2. Etiology and Clinical Presentation

Injuries to the medial collateral ligament can occur as a result of both contact and noncontact activities, usually during sports. Common examples of injuries include lateral blows to the knee which result in extreme valgus stress, as well as external rotation of the foot while the knee is flexed [2]. The latter was the injury mechanism that caused the MCL tear in the subject of this analysis.

Patients typically present with some sort of traumatic injury history to the medial portion of the knee, and most report hearing an auditory “pop” as well as feeling a tearing sensation within the knee upon injury. If a clinician suspects that the MCL has been torn, he or she can perform a valgus stress test, where the leg is extended and stress is applied medially to the knee. The clinician can then assess how much laxity is present in the affected joint, and can prescribe appropriate imaging, such as an MRI, to diagnose the severity of the injury and determine which, if any, other structures are involved.

Injuries to the MCL are graded on a scale of 1–3; grade 1 tears involve very few fibers (0–10%) and generally have no associated instability, grade 2 tears could involve anywhere from 10% to 90% of the fibers, and grade 3 tears are considered a full tear with little to no fibers remaining intact.

2. Materials and Methods

2.1. Aim

The purpose of this experimental study was to observe the effects of a single course of conservative MCL tear treatment on the static and dynamic stability of an afflicted subject. Both forms of stability were analyzed before and after a five-week physical therapy session in a single subject.

2.2. Subject

Subjects that were eligible for this study were any college-aged individual enrolled in Dr. Lockhart’s BME 598: Biomechanics and Human Physical Capability class that had recently experienced an isolated grade 2 MCL tear. The method of tear that was focused on in this experiment occurred when subjects experienced an external rotation of the foot while the knee was flexed. A total of one subject was found that met the required criteria for the study, with an afflicted left knee. Informed consent was obtained by the subject.

2.3. Apparatuses

Two devices were used to measure stability. For the static portion, an iOS app developed by Dr. Lockhart et al. was used to measure stability. The application was used on an iPhone 7 that was secured to the subject’s waist. For the dynamic portion, an Xsens MTw Awinda motion tracker with four reference points was used. One was attached to the sacrum, one to the trunk, and one on the lateral side of each shank. The subject walked around a track while a wireless receiver was carried nearby to collect data.

2.4. Procedure

The first measurement of data was taken post-injury but pretherapy. The subject had first received the injury two months prior and was awaiting a physical therapy schedule.

The subject first completed one set of static stability measurements. For four of these trials, the subject stood on both legs for 60 s with the device at their hip. Two of these were with eyes open and two with eyes closed. In addition, the subject completed one trial each standing on only one leg, with eyes open. Immediately after, the subject walked around a track (100’ × 50’) for six minutes to collect dynamic stability data. Data from the straight-line portion of this experiment was kept, while data from the corners was discarded.
After the first set of measurements, the subject completed five weeks of physical therapy twice a week. The therapy was aimed at strengthening the quadriceps, hamstrings, and triceps surae of both legs. Each session lasted 1–1.5 h and consisted of a variety of leg exercises. First, electric stimulation was applied to the quadriceps of the afflicted leg for 10 min. Following this, the subject completed 2 sets of 10 reps of each of the following: leg raises, bridges, clams, squats, and calf raises. Next, the subject completed 2 sets of 15 leg presses with 35 pounds of weight. As the subject progressed further through strength training, the intensity of exercises was increased.

Following physical therapy, the subject returned for a second set of data collection. The protocol was identical to the initial data collection performed pre-therapy. During the second data collection, the subject’s knee was taped with kinesiology tape, as part of their individualized physical therapy protocol.

3. Results

3.1. Postural Stability

The Romberg ratio (QR) is a method of analyzing postural steadiness using sway. This ratio is defined as \( \frac{EC}{EO} \) and shows reliance of visual feedback on postural steadiness. Figure 1 shows the average Romberg ratio for the pre- and post-therapy trials. The data in Figure 1 alone show little difference between the trials before and after physical therapy. More analysis needs to be done to better understand the data.

Alternate QR is \( \frac{(EC - EO)}{(EC + EO)} \times 100 \) and is used to decrease the inter-trial variance that could potentially occur during consecutive trials [4]. Figure 2 shows, for trial 1, an increase on reliance of visual feedback for stability and trial 2 shows a decrease in the reliance of visual feedback for postural balance control. Not much can be determined with confidence from this trend in velocity profiles.
Figure 2. Alternate Romberg ratio (QR) of postural steadiness sway velocity.

In the alternate QR, results close to zero or are negative shows less reliance on visual feedback for postural control.

In Figure 3, it can be seen that for trials 1 and 2, an increase on reliance of visual feedback for stability and postural balance control. This trend shows that the subject, after the physical therapy sessions, is now more apt to use their visual system over the other inputs of the feedback control loop when compared to before the therapy. This indicates a smaller reliance on the proprioceptive feedback and improvement in the subject’s steadiness abilities.

Figure 3. Alternate QR of postural steadiness sway area.

Figure 4 shows that the steadiness has increased after application of physical therapy indicating an increase in the function of the muscles involved in the single leg postural steadiness test. The subject shows a higher ability to balance on each individual leg when compared to before the physical therapy occurred. To understand how the subject is progressing in regard to the injury, it is important to analyze the ratio of the steadiness.
The ratio of steadiness of the residual legs. However, when comparing the legs to each other (RL/LL of Velocity (V) 0.98 Pre PT, 1.52 Post PT, and of Area (A) 0.96 Pre PT, 1.78 Post PT) (QR for Pre PT V = 0.99, A = 0.74 and Post PT V = 1.01, A = 0.96), Alternate QR for Pre PT V = −4.56 and A = −26.19 and Post PT V = 8.84, A = −19.1) the steadiness or stability of the subject shows a general decrease as a result of the physical therapy. This implies that the physical therapy is not beneficial to the required healing process and alternative methods of treatment should be discussed and prescribed.

Figure 4. Single leg postural steadiness before and after physical therapy.

Figure 5 shows that the ratio of steadiness of the subject decreased after the physical therapy treatments. This is indicative of a decreasing steadiness and that the therapy is not taking effect on the subject. Although individual leg steadiness may have improved, the ratio of the two has not. This could be due to compensation from the healthy leg or the subject becoming more accustomed to the steadiness tests.

The results from the static postural stability show overall improvement in stability and steadiness in terms of individual legs. However, when comparing the legs to each other (RL/LL of Velocity (V) 0.98 Pre PT, 1.52 Post PT, and of Area (A) 0.96 Pre PT, 1.78 Post PT) (QR for Pre PT V = 0.99, A = 0.74 and Post PT V = 1.01, A = 0.96), Alternate QR for Pre PT V = −4.56 and A = −26.19 and Post PT V = 8.84, A = −19.1) the steadiness or stability of the subject shows a general decrease as a result of the physical therapy. This implies that the physical therapy is not beneficial to the required healing process and alternative methods of treatment should be discussed and prescribed.
3.2. Local Dynamic Stability

The local dynamic stability was quantified using maximum Lyapunov Exponent, or maxLE. The kinematic measurements taken from four different anatomical landmarks were separately analyzed to compute maxLE. In order to isolate each gait cycle, signals with relatively clean peaks were selected for the analysis. The angular velocity recordings of foot movement in the sagittal plane were used for the right and left shanks. For the trunk and sacrum, linear acceleration in the superior–inferior direction was used. MaxLE was calculated every 50 gait cycles and the mean is shown in Figure 6 below. All four anatomical landmarks demonstrated improvement in dynamic stability, which can be seen with the decrease of maxLE from pre-PT to post-PT. Notably, two sample T-tests were performed and there was a statistically significant change in the left shank ($p = 0.004, \alpha = 0.05$), ipsilateral to the location of the injury. In both pre-PT and post-PT, the subject had relatively higher upper body stability in contrast to the legs.

![Mean MaxLE](image)

**Figure 6.** Mean MaxLE for four anatomical landmarks. Pre-PT: right shank ($1.41 \pm 0.15$), left shank ($1.36 \pm 0.10$), trunk ($0.81 \pm 0.03$), sacrum ($0.71 \pm 0.07$). Post-PT: right shank ($1.36 \pm 0.11$), left shank ($0.92 \pm 0.30$), trunk ($0.79 \pm 0.07$), sacrum ($0.69 \pm 0.06$).

3.3. Stride Duration and Cadence

The variability in the stride duration was studied to assess potential compensation mechanisms contributing to the dynamic stabilization. The mean stride duration from pre-PT to post-PT decreased with fairly high consistency as seen from the low variance. Additionally, the cadence naturally increased with decrease in stride duration. The root-mean-square of stride duration in both legs decreased from pre-PT to post-PT which suggests an improvement in neuromotor control of stride duration variability. This data can be seen in Tables 1 and 2 below. A previous study has shown that the increase in stride frequency (decrease in stride duration) can improve the mediolateral margin of stability [5]. The results may be indicative of such compensatory mechanism present in the subject, but further study would be needed to verify this.
Table 1. Stride duration.

<table>
<thead>
<tr>
<th></th>
<th>Pre PT (Seconds)</th>
<th>Post PT (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left foot Mean</td>
<td>1.106</td>
<td>1.063</td>
</tr>
<tr>
<td>Variance</td>
<td>0.001</td>
<td>0.006</td>
</tr>
<tr>
<td>Root-Mean-Square</td>
<td>1.106</td>
<td>1.063</td>
</tr>
<tr>
<td>Right foot Mean</td>
<td>1.105</td>
<td>1.063</td>
</tr>
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<td>0.0006</td>
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<tr>
<td>Root-Mean-Square</td>
<td>1.106</td>
<td>1.063</td>
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</tbody>
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Table 2. Cadence.

<table>
<thead>
<tr>
<th></th>
<th>Mean Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steps Pre PT (Steps)</td>
<td>109</td>
</tr>
<tr>
<td>Steps Post PT (Steps)</td>
<td>113</td>
</tr>
</tbody>
</table>

4. Discussion

There are two distinct possibilities for the outcome of this experiment. The first and most optimal outcome is that the subject would have shown improvements in both static and dynamic stability following the five-week interval. This would indicate that the subject’s therapy sessions had improved their postural stability for walking and standing. The other possibility is that the subject’s stability either worsened or failed to improve. In this instance, the therapy is not effective and was possibly the wrong choice for this subject. It has been found, following diagnosis, that the subject has experienced residual laxity in the medical collateral ligament as a result of their injury. In this case, surgery is required in order to repair the ligament, and they are not as likely to benefit from continued conservative treatment. While it is difficult to draw any broad conclusions from a single subject, it can be said that if there are no stability improvements for this instance, then the subject was likely administered the incorrect treatment.

5. Conclusions

Knee injuries are an orthopedic epidemic; they are suffered by people of all ages and activity levels because of the vulnerability of the knee’s soft tissue structures. The analysis completed in this study only begins to scratch the surface of biomechanical factors that can be investigated following an injury to the MCL, not to mention the fact that injuries to the other ligaments and structures of the knee each pose their own unique problems.

In addition to the tests done for this study, it would have been beneficial to perform a full gait analysis using a motion capture system and instrumented treadmill. Positional tracking would allow for estimation of the center of mass, which can then be used to calculate the margin of stability, a parameter potentially present in the control mechanism of post-PT walking. It would also be a great addendum to the study to perform another full postural and stability analysis at different points of postoperative recovery. Due to the complex nature of this study’s investigated injury (isolated MCL tear with no concomitant involvement of other structures), it is difficult to find subjects that meet this exact inclusion criteria; therefore, the study would have benefited from a larger study population. It is also worth noting that the tests in this study should only be performed if they do not cause pain or harm to the subject’s afflicted knee.

Author Contributions: K.G., M.S., T.T., and J.W. conceived and planned the experiments. K.G., M.S., T.T., and J.W. performed the measurements with academic supervision from T.L., T.T. and J.W. processed the experimental data and performed the analyses. K.G., M.S., T.T., and J.W. aided in interpreting the results and preparing the manuscript.

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References


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