Development of an ankle testing device with three degrees of freedom

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Abstract

Diagnosis of an acute ankle sprain is based in a thorough clinical examination, which can be assisted by different image modalities (sonography, x-ray, magnetic resonance imaging). However, it is still difficult to quantify the degree of injury and provide the best treatment, being the development of chronic ankle instability a major concern. With the purpose to develop a device that could objectively quantify the degree of injury, a prototype which measures the range of motion of different foot movements was built. The main goal of this work was to produce a functional prototype with three degrees of freedom, corresponding to the foot motions of plantarflexion-dorsiflexion, inversion-eversion and internal-external rotation. A positional control system was implemented to accurately control each motion. Therefore positional accuracy was tested and was found to be better than 0.3 degrees for all rotations. In conclusion, the device is ready for clinical research about mechanical instability.

Keywords: Ankle sprain, Diagnosis, Prototype, Three degrees of freedom, Positional Control System

1. Introduction

Ankle sprains are one of the most frequent musculoskeletal injuries [1]. This injury consists in the rupture or lengthening of the ankle ligaments when motion exceeds the normal physiological range, due to forces that overcome the joint’s stability mechanisms [2]. Sprains caused by the inversion movement of the foot are the most common (85%), and primarily affect the lateral ligaments of the ankle joint [3]. However several accessory injuries could occur in other tissues, such as bone or cartilage [1]. The high recurrence rate and prevailing symptoms, such as muscle weakness, pain, swelling and feeling of “giving away”, are factors of major concern and patients that suffer them have been termed as having chronic ankle instability (CAI) [4]. CAI has been described as the combination of mechanical instability and functional instability. Ankle stability is primarily due to bone congruence and ligaments restraining this bony structure. However, dynamic stabilizers are needed in order to sustain high forces generated by daily activities [2, 5]. Alterations to the anatomical structures, which are the static stabilizers, can cause hyper-hypomobility of the ankle joint. These mechanical changes comprise ankle laxity, arthrokineamatic impairments, as well as degenerative and synovial changes [5]. Functional instability is caused by in the dynamic restrain mechanism, such as muscle weakness, impaired sensori-motor system and neuromuscular system [5, 6].

After a lateral ankle sprain, any of the three joints that compose the ankle can be injured. The ankle joint is comprised by the talocrural joint, the subtalar joint and the inferior tiobiotalar joint. The talocrural joint is formed by the talus and crus bones. This joint allows the dorsiflexion and plantarflexion motion on the sagittal plane, which as a range of motion about 75° [7]. There is also a small amount of motion on the transverse and frontal planes. The lateral ligaments that prevent excessive inversion are the anterior talofibular ligament (ATFL), posterior talofibular ligament (PTFL) and calcaneofibular ligament (CFL), as can be seen in Figure 1. Being the ATFL the weakest it is the first to rupture, followed by the CFL and PTFL, respectively [1, 5, 7].

The subtalar joint is composed by the talus and calcaneus, and allows the triplanar motions of supination and pronation. Although inversion and eversion on the frontal plane, are the primary motions of the joint, with a ROM about 35° [7]. This joint is hold by the cervical ligament and the interosseous ligament (Figure 1) [4, 5]. The inferior tibiofibular joint is composed by the distal fibula and tibia, and does not allow almost any motion between the two bones. It is secured by the interosseous membrane and the anterior and posterior inferior tibiofibular ligaments [7].
The talocrural joint and subtalar joint have an equal contribution to motion on the transverse plane. Foot internal-external rotation movement is achieved by the sum of rotation on both joints, being the full range of motion about 38° [8, 9].

Diagnostic of lateral ankle sprains consists in a thorough clinical examination, where the physician asks about the episode and symptoms of the patient, as well as checking for the main signs of the injury (pain, edema, hematoma) through visualization and palpation. Manual stress tests can be used to study for mechanical instability. Different imaging modalities can be used to aid the diagnostic, such as sonography, magnetic resonance imaging, x-ray [1, 11]. This procedure is highly dependent on the physician experience and knowledge, therefore being subjective and qualitative. In order to standardize and quantify the diagnostic several ankle arthrometers have been developed, such as the Telos [12, 13], Hollis [14, 15], Lig master [11], Quasi-static Anterior Ankle Test(QAAT) [16–18], Dynamic Anterior Ankle Test (DAAT) [18, 19], Anterior Flexibility Tester (AFT) [20] and Ankle Arthrometer [3, 21].

The objective of this work was to developed a functional device with three degrees of freedom (DOF), which correspond to the foot motions seen in Figure 2. These device could aid the diagnostic of lateral ankle sprains, trough the measurement of the range of motion of each DOF.

### 2. Prototype Development

Based on the previous works [22, 23] a new prototype was conceived and design, together with a new control system for the acquired motors. Throughout this stage, all decision were made in order to get a precise, reliable and quantitative results, as well as adaptable and comfortable to any patient. The main objective for this prototype was to be able to perform the defined range of motion for each degree of freedom (Figure 2), as seen in Table 1.

#### Table 1: Range of motion (ROM) of each degree of freedom.

<table>
<thead>
<tr>
<th>Motion</th>
<th>ROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorsi-plantarflexion</td>
<td>100°</td>
</tr>
<tr>
<td>Internal-external rotation</td>
<td>20°</td>
</tr>
<tr>
<td>Inversion-eversion</td>
<td>50°</td>
</tr>
</tbody>
</table>

#### 2.1. Position Control System

The main objective of developed control system was to be able to, given a specific angle and direction (chosen by the user), the motor would rotate and stop at the previously designated position. Thus producing a rotation motion to the foot. First the control system was implemented on the dorsiflexion and plantarflexion degree of freedom, then replicated to remaining ones.

After research, the control system adequate for the desired application considering all the electronic and mechanical components, was a proportional-integral-derivative (PID) controller. A PID controller consists in a control function that actively minimizes a calculated error. For the desired positional control, the calculated error is the difference between the desired position and the actual one. The control function is the sum of three weighted...
Figure 3: Position control system based on the PID algorithm.

Figure 4: Final prototype. 1 Device with three degrees of freedom.
combination of two 3D printed parts, one where the motor is fixed and other that is fixed to the motor shaft, which will rotate together with the shaft. As can be seen in Figure 5 each DOF is composed by:

- Dorsi-plantarflexion: This DOF is composed by the tibia holder component and the dorsi-plantarflexion part. The tibia holder has two holes for straps to secure the tibia.
- Internal-external rotation: In this DOF the fixed part is the dorsi-pantarflexion part and the movable one is the internal-external rotation part.
- Inversion-eversion: This DOF is made by the internal-external part and the foot support part, which was modeled to fit the average foot size and holes for straps to lock the foot to the support.

During the design and production of the prototype, slacks and chamfers for the screws and inserted parts (fixation plates, locks of the shaft, nuts) had to be dimensioned to facilitate the assembling process and to enable motion without any disturbance.

3. Results
First each PID gain constants had to be tuned for each particular motor, this was achieved by trial and error. While this tests were conducted it was noticed that one of the GW370 motor encoder was malfunctioning, therefore it had to be replaced by the Pololu motor used in the previous work [23]. The reached values for each motor can be seen in Table 2.

After tuning, each degree of freedom was individually tested with 1 Kg weight, in order to prevent cumulative errors of assembling all the device at once, and also to check for structural errors in each component and in each DOF overall. For each DOF it was also defined an minimum velocity and an error tolerance for the stoppage positioning (Table 2), to avoid burning out the motor and braking after the desired position.

In Figure 6 it can be seen the test assembling of each degree of freedom. The test procedures consisted in ten different angles, belonging to each defined range of motion for the tested DOF. For each angle five trials were made, and the results are presented in Table 3.

4. Discussion
Manual stress tests presents high variability, due the variation of human anatomy, such as ligament flexibility, muscle strength, soft tissue thickness [30]. As well as subjectivity, relying in the physician experience to accurately detect mechani-

![Figure 5: Device part. 1 Tibia holder; 2 dorsi-plantarflexion part; 3 internal-external part; 4 foot support part.](image1)

![Figure 6: Assembling of each test. 1 Dorsiflexion and plantarflexion; 2 Internal-external rotation; 3 Inversion-eversion.](image2)

| Table 2: PID constant values obtained after tuning for each DOF. |
|---------------------------------|----------------|----------------|----------------|
| PID constants                  | Dorsi-plantarflexion | Internal-external | Inversion-eversion |
| $K_P$                          | 3.5              | 1.2             | 3.3             |
| $K_I$                          | 0.01             | 0.01            | 0.01            |
| $K_D$                          | 0.2              | 0.3             | 0.4             |
| Minimum velocity [rpm]         | 4                | 60              | 6               |
| Stoppage tolerance [$^\circ$]   | 0.032            | 0.404           | 0.027           |
Table 3: Results obtained for each degrees of freedom.

<table>
<thead>
<tr>
<th>Internal-external rotation</th>
<th>Inversion-eversion</th>
<th>Dorsi-plantarflexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Position [°]</td>
<td>Average Stoppage Position [°]</td>
<td>RMS error [°]</td>
</tr>
<tr>
<td>1</td>
<td>0.788</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.616</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4.929</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9.977</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>14.808</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20.162</td>
<td>0.292</td>
</tr>
<tr>
<td>30</td>
<td>30.020</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>39.680</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>50.101</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>60.040</td>
<td></td>
</tr>
</tbody>
</table>

*RMS indicates root mean square.*


cial instability. Also the clinical relevance of such procedures remains questionable, as they determine laxity in a single plane, ignoring the motion through the other planes [5]. Although many arthrometers have been developed neither are commonly used in the clinical procedure. Most of the arthrometers replicate the manual stress tests, therefore being susceptible to the same problems experienced in manual stress tests.

The results showed high positional accuracy in all DOFs, as can be observed in Table 3, the average final position is near the desired position. Thus having control of each DOF within the desired range of motion. The found root mean square (rms) errors were: 0.292° in internal-external rotation; 0.023° in inversion-eversion; 0.024° in plantarflexion-dorsiflexion. It can be concluded by the achieved results, that the pololu 2257 motor, does not have the same performance of the GW370, needing more power or reduction gear. Therefore this motor is only a temporary solution, till a new GW370 motor is acquired. By comparing the rms error values of both GW370 motors, one can observe that its value is very close to the stoppage tolerance, confirming that the characteristics of this type of motor is adequate for the purposed objective.

During the tests, a level was used to backup the encoders readings and also to notice structural problems, such as slack or friction between components. Some slack was noticed in the inversion-eversion DOF and the internal-external rotation DOF between the motor shaft and the lock of the shaft. This problem can be solved by glue both components or by manufacturing new ones. In order to always confirm, if the motor shaft motion is equal to the foot one, an IMU sensor could be attached to the foot support. The signal from the sensor could be used also as a second feedback signal in the PCS, forcing the motor to stop only when the desired foot position is reached.

Comparing with the arthrometers found in the literature, only the ATF measured positional accuracy, being the rms errors 1.2° for rotations and 0.5 mm [20], therefore the results obtained in this work are considered good although the testing conditions were not equal. The other arthrometers, do not seek positional control, instead a load is applied and a displacement/rotation is produce, as seen in manual stress tests (anterior drawer and talar tilt). However, testing this device on a human foot is essential to compare measured range of motion with other arthrometers, such as the Hollis which had a total inversion-eversion motion of about 59° [15].

The obtained accuracy for all degrees of freedom confers this device the ability to study not just the uniplanar rotations but also combined rotations, enabling the study of triplanar motions of the foot. As well as having the capacity to measure hypomobility and not just ankle laxity (hypermobility) as seen in other arthrometers.

5. Conclusions
In conclusion a functional prototype was produced with the aim of aiding the diagnostic of ankle sprains. However, enhancing the prototypes characteristics as implementing an IMU sensor have do be done in the future work. Finally research studies with this device measuring mechanical instability and amplitude of motion of the three degrees of freedom, should be done in order to validate its capabilities as an arthrometer.

References


