A Smart Textile Sleeve for Rehabilitation of Knee Injuries

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Abstract
A tear of the Anterior Cruciate Ligament (ACL) is a severe knee injury that requires up to a year of rehabilitation. Patients sustaining an ACL injury perform rehabilitation exercises mostly at home unsupervised. Orthopedists meet patients at time intervals as long as three months and lack quantitative ways to measure and keep track of the rehabilitation progress of each patient during these intervals. We present KneeHapp, a smart bandage and sock to support and keep track of the rehabilitation progress after an ACL injury. KneeHapp measures the quality of different ACL rehabilitation exercises and provides feedback to patients and orthopedists. We describe in detail how we constructed KneeHapp making use of smart textile technologies and provide insight into its software and quality of its measurements.

Author Keywords
KneeHapp; smart textile; e-textile; wearable; rehabilitation; knee

ACM Classification Keywords
J.m [Computer Applications]: Miscellaneous

Introduction
Tear of Anterior Cruciate Ligament (ACL) is a severe knee injury that occurs mostly among athletes. Currently, patients

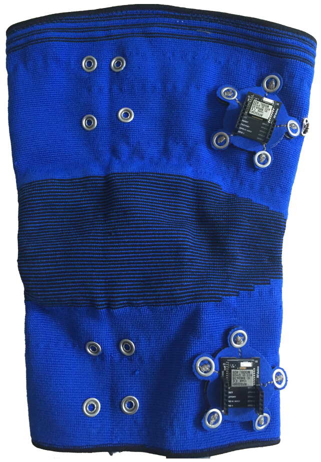

Figure 1: Outer layer the KneeHapp bandage.

Figure 2: Inner layer of the KneeHapp bandage.

sustaining an ACL injury perform rehabilitation exercises mostly unsupervised and lack ways to measure the quality and track performance of their exercising. Orthopedists also lack tools to assess patients' rehabilitation progress and still rely on subjective observations to decide on the treatment.

Different studies have investigated rehabilitation of knee injuries using wearables and mobile devices [3, 1, 4, 5]. In contrast, the application of smart textiles to support rehabilitation of knee injuries remains vastly unexplored. Furthermore, most research in the field of computed-assisted rehabilitation focuses on different injuries [1, 5, 2]. The rehabilitation of an ACL injury has a specific set of requirements which derive from the fact that most patients of ACL injuries are athletes who engage in a rehabilitation program with the goal to return to sports.

In this paper, we introduce KneeHapp Textile, a smart bandage and smart sock that support different phases of the rehabilitation of an ACL injury including the recovery of flexibility, muscle strength, and final assessment to support orthopedists determine whether patients are ready to go back to sports. We address the construction and integration of textile sensors and connections and propose software solutions to quantify ACL rehabilitation progress. KneeHapp can be used by patients to obtain feedback about the quality of their exercising and by doctors to gain information about each patient's rehabilitation progress. KneeHapp is intended to be used by patients at home.

Background

We conducted a series of interviews with two orthopedists who perform ACL surgeries on a daily basis. Based on our interviews, we identified the following problems in the current practice:

Mobility Recovery

After a knee surgery, patients lose mobility on their knees. Recovering a certain range of motion (RoM) is required before patients can continue with the rehabilitation program. During first weeks after surgery, patients need to know the degree of flexion and extension of their knees.

Strength Recovery

After the injury and during the mobility recovery phase, patients suffer from muscular atrophy on the injured leg. Therefore, the second phase of the rehabilitation focuses on muscle building. A commonly performed exercise for strength recovery are one-leg squats and different variations of it. During a one-leg squat, patients stand on the injured leg, bend it as much as they can and then go back up into their initial position without deviating their knees from the line between the ankles and hips.

Currently, orthopedists and physiotherapists lack convenient ways to measure the angle of flexion of the leg during a squat. Therefore, the performance metric currently being used is the amount of squat repetitions. However, orthopedists agree that it would be convenient to have an objective way to measure *shaking* of the leg during a squat.

Back to Sports Assessment

Towards the end of the rehabilitation, orthopedists should assess whether patients are ready to start doing sports again. In order to do this, orthopedists compare the performance of the injured and healthy legs while executing different exercises, such as one-leg hops. One-leg hop is an exercise in which patients should jump forward on one leg as far as possible and land stably. Orthopedists measure the distance of the hop by placing a meter on the ground next to the area where the patient jumps.

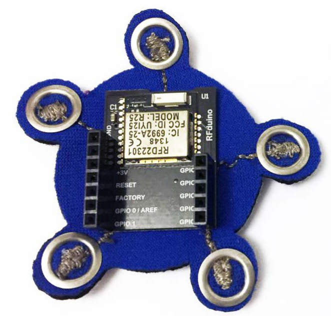

Figure 3: *Smart textile patches* hosting a microcontroller.

Figure 4: *Smart textile patches* hosting a battery holder.

KneeHapp Textile

The KneeHapp system consists of a smart compression bandage, a smart sock and an iPad App.

Smart Bandage

As a substrate for integration of the electronics, we initially considered strap bands that would be fastened to the upper and lower leg. We decided for the compression bandage for two reasons. First, patients have to wear a compression bandage after the surgery for two weeks. Second, the sensors in the bandage are placed in the same relative distance to each other. This avoids the risk of inconsistent measurements caused by a misplacement of the sensors, as might be the case when users misplace the strap bands.

The KneeHapp bandage has two layers of textile. The outer layer serves as a substrate for attachment of electronics. Two motion sensors, two microcontrollers and a coin cell battery holder are attached to the outer layer. The inner layer contains an electric circuit made of elastic conductive fiber. The inner layer also contains an integrated textile sensor that measures the amount of pressure being applied at the knee. Figures 1 and 2 show outer and inner layers of the bandage. An additional sleeve in the inner side protects the circuits from sweat and can be removed for washing purposes.

Electronic devices are sewn into *smart textile patches*. *Smart textile patches* are pieces of textile used to host an electronic device that are connected to the circuit in the bandage via metallic snap buttons. This enables users to remove the electronics for replacement or washing purposes. Figures 3 and 4 show a *smart textile patch*.

Smart Sock

The back-to-sport assessment involves mostly jump exercises. In order to gather information about the quality

Figure 5: iOS App showing the angle of flexion of the leg.

of these exercises, we integrated pressure sensitive textile material in a sock. The pressure sensitive material has been realized by mixing conductive and non-conductive fibers. When the fibers are squeezed, the conductive fibers get closer together, which causes a higher conductance of the material. Two snap buttons on the upper side of the sock connect the sock to the bandage. The pressure signal is processed in a microcontroller attached at the lower-leg.

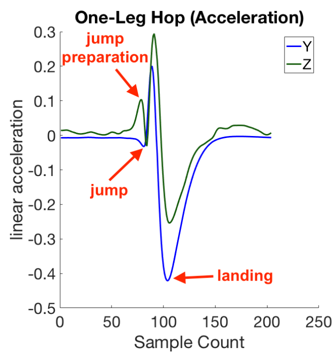

Figure 6: One-leg hop acceleration signal.

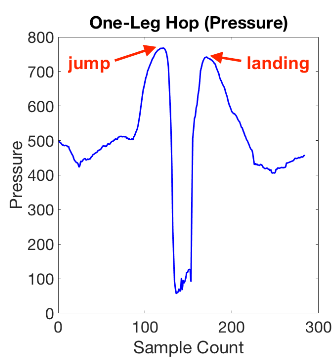

Figure 7: One-leg hop pressure signal.

KneeHapp Software

KneeHapp supports three rehabilitation phases: mobility recovery, strength recovery and the back to sports assessment.

Mobility Recovery

During the first months after the surgery, patients need to know the range of motion of their knees. KneeHapp aggregates the data from the textile pressure sensor at the knee and orientation measured by upper and lower IMUs. By convention, the angle of flexion of a leg should be equal to zero when the leg is relaxed on a flat surface. In order to account for the folding of the textile and the differences in leg anatomy and amount of swelling, we perform an initial calibration to determine the alignment of the IMUs and swelling of the leg.

Strength Recovery

KneeHapp provides live feedback to patients while performing one-leg squats in three ways. First, it calculates the angle of flexion of the leg during the squat and triggers a visual and auditive feedback when the minimal angle of the squat has been achieved. Second, it computes the degree of medial collapse of a patient's knee as the difference between the Euler angles of upper and lower IMUs. Third, it computes the degree of shaking of the leg as the standard deviation of the linear acceleration produced by the IMUs.

Back to Sports Assessment

KneeHapp measures and keeps track of the performance of one-leg hops. The duration of a one-leg hop is estimated based on data from the IMUs and pressure sensor in the smart sock. Figure 6 displays the linear acceleration signal produced by the upper IMU and Figure 7 displays the pressure signal measured by the smart sock during a one-leg hop.

Conclusion

In contrast to most computer-assisted solutions for rehabilitation, KneeHapp makes use of smart textile technology to address robustness, user comfort, energy consumption and modularity. The information measured by KneeHapp Textile could be used to keep track of the motion recovery after the surgery and to help orthopedists determine the degree of recovery of the injured leg.

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