SoPhy: A Wearable Technology for Lower Limb Assessment in Video Consultations of Physiotherapy

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ABSTRACT
Physiotherapists are increasingly using video conferencing tools for their teleconsultations. Yet, the assessment of subtle differences in body movements remains a challenge. To support lower limb assessment in video consultations, we present *SoPhy*, a wearable technology consisting of a pair of socks with embedded sensors for patients to wear; and a web interface that displays information about range of weight distribution, foot movement, and foot orientation for physiotherapists in real-time. We conducted a laboratory study of 40 video consultations, in which postgraduate physiotherapy students assessed lower limb function. We compare assessment with and without *SoPhy*. Findings show that *SoPhy* increased the confidence in assessing squats exercise and fewer repetitions were required to assess patients when using *SoPhy*. We discuss the significance of *SoPhy* to address the challenges of assessing bodily information over video, and present considerations for its integration with clinical practices and tools.

Author Keywords
Video communication; clinical consultation; physiotherapy; bodily communication; wearable technology.

ACM Classification Keywords
H.4.3 Communications Applications: Computer conferencing, teleconferencing, and videoconferencing.

INTRODUCTION
Physiotherapists are increasingly using video conferencing tools to conduct consultations over-a-distance [13,14,30,40]. Yet, despite the benefits of transcending long distances, video consultations limit access to bodily cues and reduce clinician's confidence in accurately assessing the patient. Consequently, the treatment offered by physiotherapists over video is less specific than that given in face-to-face consultations [3].

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Lower limb movements are particularly, difficult to assess over video because video conferencing tools are typically configured to support talking heads conversations. Video conferencing tools have little consideration for the observation of full body movements [22]. Physiotherapists find it difficult to assess lower limb movements such as weight distribution, fatigue, and details on exercises that involve multiple joint movements (e.g., squats) [3]. While computer vision techniques are explored significantly in physiotherapy [18,28], these approaches have limitations in capturing the subtleties of movements, especially related to lower body [18,39]. We, therefore, explore the potential of a wearable device to enhance video consultations.

We present a novel wearable technology, *SoPhy* that can capture lower body movements during video consultations of physiotherapy (Figure 1). *SoPhy* consists of (1) a pair of socks for the patient to wear, which contains three pressure sensors and one Inertial Measurement Unit to capture lower body movements, and (2) a web interface that visualizes information about weight distribution, range of movement and foot orientation to physiotherapist in real-time.

We conducted a laboratory evaluation to investigate how *SoPhy* helps physiotherapists in their assessment of lower limb movement. The evaluation was based on 40 simulated assessments through video consultations across two rooms in a laboratory setting. The assessments were conducted by

Figure 1: The wearable components of *SoPhy:* Each sock consists of three pressure sensors and one IMU.

10 postgraduate physiotherapy students. Each participant performed four assessments– two each with and without *SoPhy*. The findings suggest that *SoPhy* increased the confidence of participants in assessing squats. Fewer repetitions were required for assessment when using *SoPhy*. For patients with low pain, *SoPhy* helped in comparing the subtle differences in feet movements, while for extreme pain conditions, *SoPhy* served as a training tool.

This paper makes the following contributions: First, we developed *SoPhy*, a novel system to extend video consultations with precise information about body movement. Second, we contribute a study of our system, which highlights the utility of visual feedback to help assess lower body movements. Finally, we identify a set of challenges and design considerations to integrate this feedback with clinical practices and tools.

RELATED WORK

Video Consultations

Over the last decade, video consultation has emerged as a recognized practice to offer diagnostic and therapeutic advice to patients who otherwise, have limited access to health service [13,14,30,40]. Clinicians and patients utilize video conferencing tools, like Skype, for the purpose of communication. Video consultations are used in a variety of clinical domains, such as surgery [35], physiotherapy [3], autism education [4], and knee rehabilitation [30].

As yet, video consultation systems predominantly utilize audio and video to support communication with different setups like multiple screens [35] and interactive walls [25]. Recent study [3], however, challenged the applicability of audio-video media for physiotherapy consultations. This study demonstrated that physiotherapists either miss the crucial bodily cues altogether or do not get sufficient details about body movements because of the limited visual acuity offered by video technology. The absence of the essential information reduced clinician's confidence in suggesting new exercises to patients, and they were limited to tweaking previously recommended exercises in video consultations.

Previous works have emphasized the need to communicate essential bodily cues to the clinicians, the absence of which influences the treatment outcome and clinician-patient relationship [9,36]. The lack of clinician's confidence may reduce patient's trust on the clinician and adherence to the treatment [36]. Furthermore, Lee et al. [21] expressed the fear of dehumanizing clinician-patient relationship with limited ability of clinicians in making decisions over video. While there is evidence that video technology does not support all the essential information that clinicians require [3,11,26], lesser attention is paid to explore technologies that could support clinicians in their assessment. Below we discuss the existing technologies that could potentially support physiotherapy related video consultations. However, these technologies have certain limitations, which motivated us to design a novel wearable technology, *SoPhy*.

Technology for Rehabilitation

There is a growing interest in body tracking technologies to support rehabilitation [28]. This is typically undertaken with automated pose detection and estimation techniques using computer vision approaches. Technologies like Microsoft Xbox Kinect [18] and Vicon motion tracking cameras [37] are used to guide patients to complete their rehabilitative routines without the supervision of physiotherapists. Along the similar vein, Hoang et al. [17] explored the opportunities with virtual reality environment to guide students on body postures for remote sessions. However, these technologies have limitations in capturing the fine-grained movements, such as range of joint movements and body orientation [18,39]. Details about these fine-grained movements are particularly relevant to accurately assess the biomechanics of lower limb.

Capturing lower limb movements in video consultations is challenging. It requires different camera orientations to accurately render depth and perspective. Also, focusing the camera on specific body parts may limit other crucial information related to patient's full body posture, and facial expressions that clinicians look for to understand patient's recovery [3]. To accurately capture lower limb movements, there have been studies [5,6,20] that utilize sensors to track and visualize knee angles during exercises. These systems present the captured information on a computer screen [6, 20] or directly on a wearable device using lighted fabric [5]. For example, BASE [12] is an ankle work sensor that is designed to improve lower limb strength and balance of elderly people. The system provides both visual and audio feedback to users for home rehabilitation.

Other related work concerns sensing socks, shoes and boards to support low-limb rehabilitation. For instance, as people with foot ulcers get little sensations in their feet, pressure sensing socks [10,27] and shoes [31] are developed to prevent them from hurting themselves. Some attempts are also made to help people in improving their postural stability (e.g., Sensoria Fitness Socks [32]), and to offer better understanding of one's own body [38]. Nintendo Wii [24] is another popular device to capture weight distribution for standing positions. However, these systems are either not commercially available or do not provide open API to adopt the software as needed. Additionally, these systems are not specifically designed to support video consultations. Therefore, the visual output is presented locally on a mobile or computer screen and not available to access remotely.

Considering the prior success of sensor-based socks in clinical settings [27], we explored the use of socks to support lower limb assessment in video consultations for physiotherapy. Also, as socks conform to the body and move along with the patient, we can accurately capture the dynamicity of a physiotherapy session where the patient performs a variety of static and dynamic exercises [3,6]. Next we discuss the developed wearable system, *SoPhy*.

SOPHY

SoPhy (pronounced as Sophie) stands for 'Socks for Physiotherapy'. *SoPhy* is a wearable technology that is designed to support lower limb assessment in physiotherapy related video consultation. *SoPhy* has two parts: first is a pair of socks containing three pressure sensors and one Inertial Measurement Unit (IMU) to capture lower limb movements (Figure 1); second is a web interface that presents information related to weight distribution, foot orientation, and range of movements to physiotherapists in real-time (Figure 2).

Patients wear the *SoPhy* socks before starting the video consultation with physiotherapist. During the video consultation, the physiotherapist asks the patient to perform lower body exercises (e.g., squats, and tip toes). As the patient performs the prescribed exercises, the socks capture data about foot movement. This data is then sent to the web interface, where the physiotherapist can see this information in real-time. We designed a mobile app to support the communication between the socks and web interface, via a Bluetooth shield [34] attached on the socks. As such, the *SoPhy* socks capture data about the *weight distribution*, *foot orientation*, and *range of movement* in the following way:

Weight Distribution: Weight distribution describes how much weight a person is bearing at different points on the sole of the foot e.g., on toes, balls, and heel. A healthy person distributes their weight equally on each foot. However, the pattern changes if the foot is injured. For example, if the big toe of a foot is injured, the person may bear more weight on the outside of the foot.

SoPhy captures the pattern of weight distribution across the balls and heel of the foot using pressure sensors sewed on the socks. Corresponding to each sensor, the weight distribution is represented by the colors and numbers shown on a sketch of the underside of the feet (refer the lower half of Figure 2). The color spectrum denotes the measure of weight on each point, while the number shows the pressure values on a scale of 0-30.

Foot Orientation: Foot orientation refers to the alignment of foot in four directions.

- *Dorsiflexion* occurs when the person bears weight on the heel of the foot.
- *Plantarflexion* occurs when the weight is on the balls and toes of the foot.
- *Medial orientation* when the weight is on the inside of the foot and the person lifts the outside of foot up in the air.
- *Lateral orientation* is when the person bears weight on the outside of the foot and lifts the inside of the foot up in the air.

Foot orientation is captured by an IMU mounted on the socks at the bridge of the foot. For the web-interface, we used ten sketches to display the foot orientation: three each for dorsiflexion and plantarflexion, and two each for medial and lateral orientation. These sketches change in real-time based on the captured data (refer upper half of Figure 2).

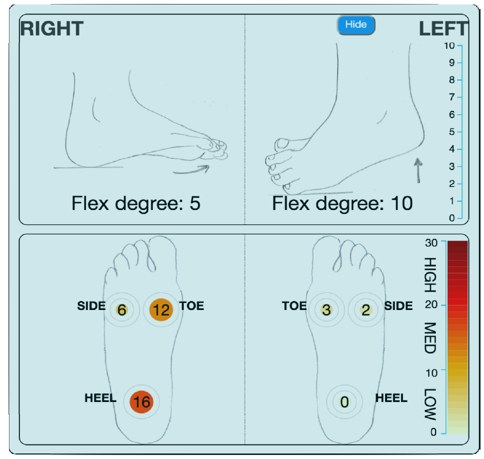

Figure 2: The *SoPhy* web-interface displays information about the weight distribution, foot orientation and range of foot movement.

Range of Movement: Range of movement refers to the magnitude of foot orientation across four directions described above. The range is defined on a scale of 1 to 10 and is calculated from the IMU data. On the web-interface, this value is represented as a 'Flex degree' under each foot.

DESIGN PROCESS

The final design of *SoPhy* was the result of multiple explorations and e-sewing trials over a 6-month period. The different phases of scoping the problem and iterating socks and web interface are described here in a linear order for clarity, but in practice they were intertwined.

Scoping the Problem and Ideation

The problem was initiated through collaboration between the University of Melbourne and the nearby Royal Children's Hospital. The physiotherapist at the hospital (author Mark Bradford) has been conducting video consultations for over three years. From our previous study [3], we identified the following lower body cues that were crucial to assess leg exercises over-a-distance: weight distribution, range of movement, depth, fatigue, smoothness of movement, and posture.

Together, we brainstormed ideas about how to best capture these cues. We explored various sensor technologies (e.g., flex sensors, accelerometers, ultrasonic band) and where to position these sensors on the body. These ideas were rendered as design sketches and discussed with the physiotherapist to assess their merit. Two bodily cues were discarded after brainstorming: posture was excluded as it can be observed over the video; and fatigue was excluded as a person can feel tired for multiple reasons not related to medical conditions. The physiotherapist affirmed that weight distribution, foot orientation, and range of movement would offer valuable insights that are not easily

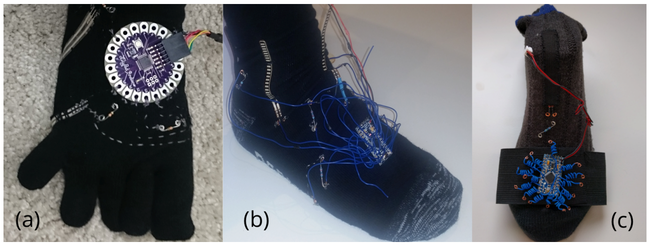

Figure 3: Early iterations of *SoPhy*: (a) Toe socks (b) normal socks with 4 flex sensors (c) normal socks with 1 flex sensor.

available over video. We also discussed the body positions for sensors, and learnt that the weight of a healthy person is predominantly distributed over the balls, heel and big toe of the foot. Hence, we chose these three locations for sensors to gauge the best understanding of weight distribution.

Ongoing discussions with the physiotherapist as well as with engineers and designers in our research center were critical in developing ideas for the design of *SoPhy*. In a second meeting with the physiotherapist, we discussed the calibration of sensors for different foot sizes, and the potential visualisation of the captured data. We asked the physiotherapist to try out the socks and comment on wearability. In the last meeting, we role-played a video consultation with a sock prototype and paper prototypes of data visualisations to evaluate their clarity and usefulness.

Iterations of the *SoPhy* Socks

We started our design process from identifying the right sensors to capture the required data. We selected Flexiforce Pressure Sensor [15] for capturing weight bearing on the foot. Initially we aimed to capture pressure values on each toe to give us rich data about weight distribution (Figure 3a). However, given the small surface area of toes, sewing pressure sensors on toes and avoiding short-circuiting of connections around LilyPad were challenging. Hence, we reduced the number of sensors to three: one on each ball and one on the heel. Reduction of pressure sensors then affected our choice of socks and we then used the regular socks (see Figure 1 for the final design).

Capturing range of movements however, required multiple iterations, as there are different sensors available for this task. In the beginning, we explored the use of flex sensors [16] because of the ease to process the captured data. We tested flex sensors by sewing four of them on socks around the ankle (Figure 3b). However, owing to the limited movement around ankle, the flex sensor was not sensitive enough to capture the movements. Finally we opted for the Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout [1]. IMU provides data points across xyz coordinates, which we processed to derive values of foot orientations and range of movement.

We tried two microcontrollers: LilyPad [23] and Arduino ProMini [2] to capture the data from the sensor. We opted for Arduino ProMini, as it is smaller in size, therefore, easy to accommodate on the socks; and it has more analog pins

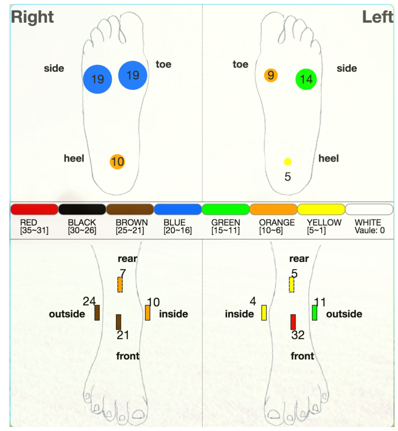

Figure 4: Previous interface with flex sensors visualisation.

to wire in sensors. However, it raised issues of short-circuiting as all the pins were very close to each other. To avoid short-circuiting issues, we used thin conductive wires to make connections (Figure 3b, 3c). However, exposing wires on socks made it look less wearable. Hence, in the final design we covered all connections to Arduino underneath several layers of clothes (see Figure 1).

Iterations of the *SoPhy* Web-interface

For the web interface, we explored different ways to present the sensor data. We initially considered using photos of the underside and the side of the foot to provide a realistic visualisation. However, we chose sketches instead to simplify the visualisation and to make them neutral for age and gender. Being smaller in size, using sketches also improved the latency of updating the web-interface in real-time based on the sensor data. We also switched from using foot sketches of the front view (Figure 4) to side view (Figure 2). Because side view provides a different perspective of the patient's feet to clinicians as opposed to the front view, which is already available in a typical video call. The other change for the web-interface was the use of a color spectrum to maintain visual consistency. The final design of the web interface is shown in Figure 2.

EVALUATING SOPHY

We conducted a laboratory study to investigate how *SoPhy* helps physiotherapists in conducting lower limb assessment during video consultations. Taking inspiration from prior works [21,35], we simulated video consultation settings to evaluate *SoPhy,* but aimed to mimic the structure of video consultations as closely as possible. To this end, we organized the consultation across two rooms in the lab. We used Skype to arrange video conferencing, as it is one of the standard tools at the collaborating hospital. The study was approved by the university ethics committee.

Participants

We recruited participants to play two types of role: 1) the physiotherapist and 2) the patient. Participants were recruited from the university's mailing list.

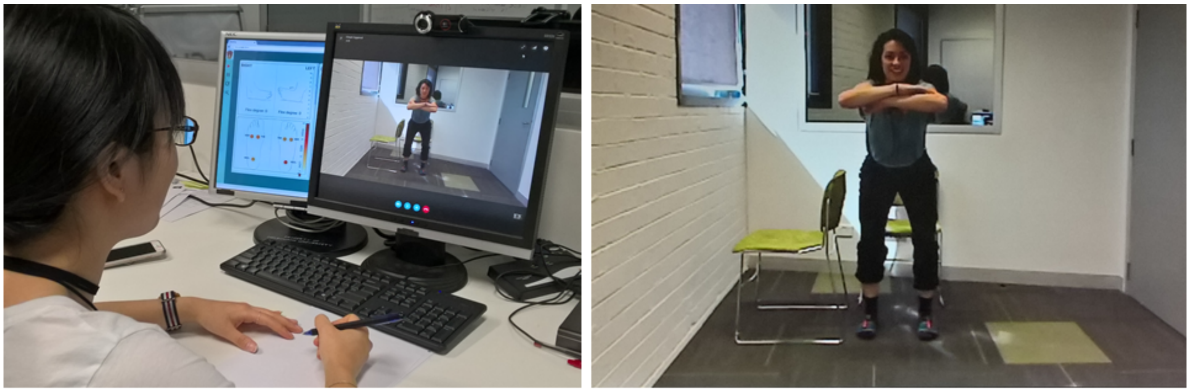

Figure 5: Study setup- In left, a participant using *SoPhy* interface during a video session. On right side: the actor is performing squats wearing *SoPhy* socks.

For the physiotherapist role, we recruited 10 students (3 male, age range: 23-28 years) from the second and final year of the postgraduate physiotherapy degree at our university. For this role, participants were expected to have completed formal training on standard patient assessment and treatment relating to different issues in their study. As part of the degree program, participants had prior experience in role-playing different patient profiles to learn assessment and treatment. They had completed 37 weeks of clinical practice at hospitals where they assisted physiotherapists in treating patients. We utilized their skills to evaluate the utility of *SoPhy* as asking them to play the role of physiotherapists in the evaluation. No participant had prior experience with video consultation or wearable technology. The participants received a $20 gift voucher.

For the patient role, we hired a final year physiotherapy student (female, 28 years old) to play the role of patient for the entire study to get consistency (in line with the earlier study [17]). We refer to the patient as actor to avoid any confusion with our participants. We appointed her as our candidate because of her prior experience in assisting physiotherapy sessions as well as her consistency in performing the exercises for different patient profiles. We conducted training sessions with the actor to train her for different patient profiles. The actor was paid $25 per session for her participation in the study.

Study Design

The study had four conditions involving video consultations "*with SoPhy"* as the test condition, and standard video consultations "*without SoPhy"* as the baseline condition. The actor and the participants were located in two different rooms. In both conditions, communication was conducted through a Skype video call. In the *with SoPhy* condition, in addition to the Skype screen, participants were presented with the visualisation interface of *SoPhy.* Figure 5 provides the details of the study setup.

Independent Variables

The independent variables were the *consultation technology* (*with SoPhy* and *without SoPhy)* and *pain levels* (*extreme pain* and *low pain)*. Based on these independent variables, we designed a 2x2 within subject study with four conditions: *with SoPhy-extreme pain*, *with SoPhy-low pain*, *without SoPhy-extreme pain* and *without SoPhy-low pain*.

Dependent Variables

For each consultation, we asked the participants to evaluate six exercises. For each exercise, participants filled out a Patient Assessment Form with the following factors: *weight distribution, foot alignment, range of movement,* and *confidence.* We also counted exercise repetitions from the video recordings. These factors are the dependent variables of the study.

Tasks Performed by the Participants

Each participant was asked to conduct four consultations: two each with and without *SoPhy*. We randomized the order of these sessions to avoid any learning effect. Also, we created different patient profiles to makes these sessions realistic, which we discuss later. In all four sessions, participants requested the patient to perform six exercises and filled out the Patient Assessment Form (discussed in next section). After four sessions, we interviewed the participants to understand their overall experience with *SoPhy.* Participants took around 2 hours to finish the study.

Tasks Performed by the Actor

The actor was instructed to perform the following six exercises based on the patient profile: dorsiflexion, plantar flexion, double leg squats, double leg heel raises, single leg heel raises, and walking. Dorsiflexion and plantar flexion were performed while seated, and rest exercises were performed in standing. Figure 6 shows a snapshot of these exercises. We selected these exercises after consulting with a physiotherapist (last author) to ensure that the exercises represent the clinical practice, and that they were are not physically demanding for the actor to perform repeatedly.

Patient Profiles

Because each participant conducted four consultations, we created four separate patient profiles such that they find every patient as unique, without any learning effect.

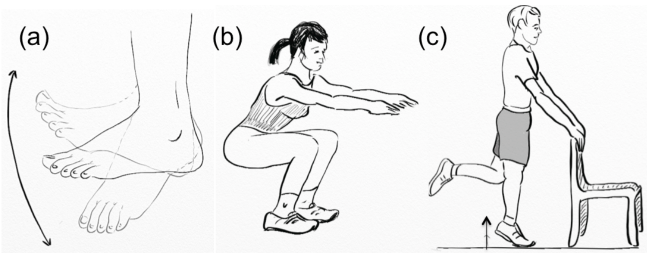

Figure 6: Description of exercises: (a) Dorsiflexion and Plantarflexion, (b) Squats (c) Single leg heel raises.

The patient profiles were created around two pain levels: extreme pain and low pain, which were created in consultation with the last author. We limited the profiles to extreme and low pain to study the utility of *SoPhy* in assessing contrasting movements, while keeping the study design simple. These extreme opposites also made it easier for the actor to consistently perform the respective roles.

Table 1 illustrates the names for each profile where Sam and Veena had similar injury in left foot, while Susan and Vicky had similar injury in right foot. The order in which each participant sees the patient profiles was randomized.

Participants were provided with the background details of each patient that described the cause of injury and how it has changed over the period of time; whereas the details of the pain and other socio-emotional factors that define movements were only provided to the patient. Table 2 shows details of the two patient profiles for extreme pain. For these profiles, we presented the following information to the actor: asymmetric walking with less weight on heel of the left foot, fearful of walking and touching, constant pain, swelling in ankle and outside of left foot, extreme pain today with pain level 5 (on a scale of 0 to 6).

For all patient profiles, video sessions were described as follow-up of face-to-face consultations. Also, all patients were described as already following on the six exercises from the last consultation along with the number of repetitions - five for extreme pain and ten for low pain. Therefore, participants did not have to explain these exercises to the patient in these sessions.

Data Collection

Since the aim of this project is to support the work of physiotherapists in video consultations, we mainly collected data from our participants. We also discussed with the actor about her experience with *SoPhy*. Following on the existing works on physiotherapy [33,37], we employed a mixed

Pain Profiles	*with SoPhy*	*without SoPhy*
Extreme pain	Sam	Veena
Low pain	Susan	Vicky

Table 1: We created four patient profiles: two each for with and without *SoPhy* based on two pain levels.

Sam is a 16-year-old girl who works as a helping hand in a restaurant. Last year, she twisted her left foot during a busy day at the restaurant. After the incident, Sam feels pain around ankle. The pain is not constant, but on days when she has it, it gets unbearable. She has consulted many clinicians as yet, but the pain does not seem to go away. Veena is a 15-year-old high school girl who was very active in sports until 2 years back when she twisted her left foot ankle. She has been on pain medication for 4 months and has consulted psychiatrist and surgeon. She has recently started physiotherapy to get rid of her pain. She is diagnosed with chronic pain in left foot ankle.

Table 2: Details of the two patient profiles for extreme pain.

method approach where we collected from four sources. Firstly, we video-recorded the sessions and we observed participants to understand their interactions with *SoPhy.* Being present with the participants allowed us to reflect upon the latest event in a think-aloud manner. Participants also filled the Patient Assessment form during each session, which we discuss below. Finally, we conducted a semi-structured interview with participants to understand their overall experience with *SoPhy*. All interviews were audio-recorded and field notes were written for later analysis.

Patient Assessment Form

We designed a Patient Assessment Form for data collection, modeled after the assessment form of the collaborating hospital and changed it as per the study goals by consulting the last author. Each participant filled one form in each session (four in total).

The form provided background information of the patient (as shown in Table 2), and required the participant to fill in the patient's pain intensity on both feet (on a scale of 0 to 6). The participant had to inquire the patient about their pain in order to fill this information, which provided a starting point for them to initiate the consultation process.

For each exercise, participants were asked to fill in the following information for each foot: weight distribution, foot alignment, range of movement, and confidence in assessment. For each factor, the participant marked a selection on a scale of 0 to 6. We provided labels for value 0, 3 and 6 for coded data. For weight distribution, participants assessed the pattern of weight distribution over each foot (labels: heel, middle, and balls). Similarly, participants assessed the foot orientation (labels: medially, balanced and laterally) and range of movement (labels: none, partial and complete) over each foot. Confidence assessment was a self-rated value with labels: lowest, medium, and highest.

The final section was dedicated to write notes about the body posture of the patient and a rating of confidence value with the overall assessment.

Data Analysis

We performed thematic analysis [7] on the field notes and interview transcripts. We coded the data on paper and created memos to capture ideas and trends emerging from the data about the interactions with *SoPhy*. We manually analyzed the video recordings to calculate the number of repetitions of each exercise.

We performed nonparametric factorial ANOVA analysis using the Aligned Rank Transform tool in R [42] on the factors *consultation technology* and *pain level*, and the interaction effect of *consultation technology**pain level* on the dependent variables: *weight distribution, foot alignment, range of movement*, *confidence assessment,* and *exercise repetition*. The analysis helps us to determine if the usage of *SoPhy* would affect the decision making process of physiotherapists. Using affinity diagrams, we structured key findings into five themes that we discuss next.

FINDINGS

Below we discuss the findings across five themes. We have used participant IDs (P1, P2 ...) to denote their quotations.

Increased Confidence in Assessment

The findings show that participants were more confident in their assessment when using video consultation *with SoPhy* and *without SoPhy*. For squats, there was a main effect of consultation technology on confidence ratings ($F(1,36)=10.97$, $p<.01$). *SoPhy* increased the confidence of participants in assessing squats (M=5.75, SD=1.06), as compared to the video consultations *without SoPhy* (M=4.17, SD =1.13).

The qualitative data showed that *SoPhy* was critical to confirm initial observations made through the video data. All participants developed a strategy to observe the required information from both video stream and *SoPhy* interface. They formulated an initial assessment by first observing a couple of repetitions from the video stream and then utilized the *SoPhy* interface to verify their hypothesis: "*The sock system was more like a confirmation for me. I used the strategy of first seeing the video and then form an assessment. After a couple of repetitions with video, I used the interface to confirm my assessment.*" (P8).

SoPhy reduced the need for verbal confirmation with patients and the ambiguity created by such dialogues. While participants sought verbal confirmation for their assessment in the consultation *without SoPhy*, e.g., "*It seems like you are not putting more weight on the outside of your left foot"* (P2), there were no such verbal confirmations *with SoPhy*.

Participants described that they felt more confident in their assessment with *SoPhy*. This removed the need for verbal confirmation and potential ambiguity it may bring, as discussed by participant 2: "*I did get more confident in my assessment with the socks data. Without it, I may not be able to pick up things just from video. Like I thought, 'Oh that foot looks tilted outside', but then whether it has any relation with their weight distribution or not, I can't tell just from the video. Confirming with the patient is not very helpful as they might not know what's going on with them."*

Fewer Exercise Repetitions Required to Assess Patients

The participants reported that with *SoPhy* they needed fewer repetitions of exercises to assess patients compared with the standard video consultation. The analysis of the video recordings showed that *SoPhy* required 30-40% fewer exercise repetitions than the *without SoPhy* condition as shown in Table 3.

Exercises	***With SoPhy***	***Without SoPhy***
Dorsiflexion $F(1,36) = 6.99$, $p<.05$	M=8.10, SD=3.21	M=11.25, SD=4.54
Plantarflexion $F(1,36) = 6.14$, $p<.05$	M=7.45, SD=3.88	M=10.60, SD=4.24
Squats $F(1,36) = 8.36$, $p<.01$	M=6.05, SD=2.48	M=8.05, SD=3.18

Table 3: *SoPhy* required fewer repetitions for assessment.

One reason for the reduced number of repetitions was the increase in confidence in patient assessment with *SoPhy*. In the interviews, participants felt more confident in their assessment after only a few repetitions when using *SoPhy*. "*With sock system, I realized I got good information quite early, which was really good. I did not push her way too much then, which is what I will do with real patients. Therefore, I was more confident then.*" (P3)

A second reason was that *SoPhy* alleviated the need to ask patients to perform exercises with different camera angles. Rather than asking patients to reposition the camera to see specific body movements, *SoPhy* offered rich information equivalent to multiple camera view points: "*Over video, I can't see what's going on behind the foot, especially for exercises like plantarflexion. I can see the person only from one direction. The system provides me this detailed information irrespective of how the person is standing or sitting. Of course you can ask the person to turn around, but unless you are right there you would not understand what is going on. I did not ask the patient to turn backwards or sideways when I had the sock data. The system was already doing it for me.*" (P3)

Reducing the number of repetitions is important especially, for patients in extreme pain, as it helps clinicians to avoid movements that could inflict further pain to the patient. "*If a person is in extreme pain, I wouldn't ask them to do more exercise. I wouldn't want them to keep going otherwise, they will lose trust in the therapy."* (P3)

Weight Distribution Offers Hitherto Unavailable Insights

Weight distribution was the most useful information provided by *SoPhy*, i.e., because it provided hitherto unavailable information for participants. Range of motion and orientation presented by *SoPhy* offered a more detailed understanding of these issues and increased confidence in assessment, but these measures were largely inferred from the video alone. Unlike range and orientation data, there is no direct way to observe weight distribution. Participants reported that in face-to-face assessments, they rely on indirect clues to understand weight distribution, e.g., *"from the noise they are making while walking"* (P5). However, such clues vary based on different factors (e.g., shoe sole, and weight bearing) and are difficult to observe over video.

Hence, the weight information provided by *SoPhy* offered a novel, direct way to assess patients. The visualisation not only helped them to understand which foot is bearing more weight, but also how weight is distributed across each foot. "*It's always challenging to understand weight bearing because the pressure points are not visible. The socks data certainly helped in that way. It's easy in cases when the person is putting more weight on one foot than other. But it is difficult to understand how the pressure is distributed across the foot, is it on the heels, or on the balls.*" (P8)

The information of weight distribution also offered insights into the lateral and medial orientation of foot, which are difficult to observe. One participant described the difficulty that she faced in checking the foot orientation in sessions with standard video consultation: *"When I asked the patient to turn sideways to see the lateral and medial alignment of the foot, the front leg obstructs the other leg. It's harder to see both legs at the same time from here."* (P7)

Another participant described how *SoPhy* helped him to understand these orientations: "*The values of weight distribution were sufficient for me to know that the person is moving laterally or medially. The numbers tell me that the person has pressure on the outside, inside or at the back. So then visually I can get that if the pressure is on the outside, meaning she is going laterally."* (P10)

The statistical analysis further underlined the difficulty of assessing weight distribution and the difference that *SoPhy* makes here. The analysis showed that there is a significant difference in assessing the lateral and medial alignment of the affected foot between *with SoPhy* and *without SoPhy* conditions: dorsiflexion ($F(1,36)=4.30$, $p<.05$), double leg heel raises ($F(1,36)=7.63$, $p<.01$) and single leg heel raises ($F(1,36)=25.50$, $p<.001$).

The interaction effect between *consultation technology* and *pain level* was significant for the medial and lateral alignment factor for dorsiflexion ($F(1,36)=4.30$, $p<.05$) and squats ($F(1,36)=12.70$, $p<.01$). We then performed two Wilcoxon signed-rank tests using Bonferroni adjusted alpha level of 0.025 per test (.05/2), to analyze the effect of *SoPhy* within each pain level for dorsiflexion and squats. For squats, there was a main effect of *SoPhy* on assessing the alignment in *extreme pain* condition, ($Z=3.92$, $p<.025$). There was no other significant pairwise comparison found.

It is important to note that the results do not indicate the assessment being more accurate, as there is no benchmark to make this comparison. However, the difference in the assessment highlights that *SoPhy* did not merely confirm assessments made via video, but that it also helped in assessing weight distribution for different foot orientations.

Pain Levels Influenced Assessment with *SoPhy*

The level of pain experienced by patients is an important factor for physiotherapists because it affects their choice of exercises and repetitions to recommend to patient. We found that the pain level had significant effects on alignment assessment throughout all exercises: dorsiflexion ($F(1,36)=27.70$, $p<.001$), plantarflexion ($F(1,36)=29.90$, $p<.001$), squats ($F(1,36)=9.75$, $p<.01$), double leg heel raises ($F(1,36)=30.06$, $p<.001$) and single leg heel raises ($F(1,36)=20.06$, $p<.001$).

Participants stated that they used *SoPhy* differently depending on the pain condition. In extreme pain, participants focused more on training and motivating the patient to perform movements, where *SoPhy* could be used as a feedback for patients: "*In extreme pain, the system might be more useful for patients to see what's happening. So they could see that they are scoring 3 on that affected area whereas it's 18 on the other foot for the same location. In pain, quite a lot of sensations get mixed up and they are not able to distinguish the difference. Now through numbers, you can talk through what they are doing as opposed to what they should be doing."* (P5)

For low pain conditions, participants described that the aim of physiotherapists is to optimize patient's movements with focus on subtleties, such that they could get back to their normal movements. Here, *SoPhy* will help in making comparisons on the patient's recovery. One participant highlighted the challenge of bringing the patient back to the normal movements and how the system would help: *"In pain, people change the biomechanics of their body to allow them to do different activities. They might have developed some secondary changes down the road. Like to walk, they kind of hit the ground and then pull the foot in some sort of fashion. It's harder to eyeball all these tricks, and you can't even confirm it with the patient. That's where the numbers [from SoPhy] will help me to see whether there is any improvement in the patterns or not."* (P10)

Challenges in Mapping Information with Observations

The findings also highlighted several challenges in interpreting the information provided by *SoPhy* with observations from the video. Several participants reported that it took them a while to learn how the system works and how to relate the information presented by *SoPhy* to the information gleaned from the video. *"It was a little bit distracting in the beginning when you don't know what to see when. I spent too much time looking at the numbers without much looking at what the patient was doing."* (P10)

The main challenge was to map the information offered by *SoPhy* with the movements visible over video stream. The visualisations offered by *SoPhy* were presented on a different screen to the video and simply looking at the visualisation did not provide sufficient information. "*When she was walking, I wanted to see her gait but I also wanted to check the numbers. But when I see the numbers on the other screen, it is difficult for me to understand what data corresponds to which movement.*" (P7)

Mapping left and right foot between video and *SoPhy* was also found confusing: "*Mapping the left and the right side is the biggest challenge like in video the right foot of the patient is my left foot. And then on the other screen [SoPhy interface], I need to do this mapping again.*" (P4)

Additionally, the presentation of the range of movement was found confusing. *SoPhy* presented a flexion degree (a number between 0-10) whereas participants measure the range as an angle (e.g., 70 degrees) from the starting point to the end point of a given movement. "*Right now the system gives me some numbers for range. I do not know what these numbers are, whether it's positive or negative like dorsi data is a positive angle for me, while the plantar angle is negative.*" (P10)

Finally, for some participants the sock was interfering with their observations from the video. While the sock helped in capturing new information, it also concealed information about the foot structure that participants could observe in the standard video consultation. "*The biggest issue with a sock is that it covers the foot and it is hard to see the foot moving. With socks, you see the foot as a plank but there are so many joints moving for one movement. Not being able to see the foot may not be an issue for all conditions, it is more important for injuries in toe as you might want to see how the toe is placed, or is it moving at all or not." (P6)*

DISCUSSION

SoPhy enhanced the effectiveness of physiotherapy video-consultations through hitherto unavailable information related to lower limb movements. Firstly, participants felt more confident in their assessment when using *SoPhy* compared to standard video consultations. Increasing confidence in assessments is crucial because it impacts consecutive diagnosis and treatment of the patient [9,36]. Furthermore, lack of confidence can also negatively affect the patient's trust in their diagnosis and their adherence to the treatment [36]. Secondly, fewer repetitions were required when assessing with *SoPhy* than in standard video consultations. This is particularly, useful for patients having extreme pain, as fewer repetitions will reduce the discomfort experienced by the patient during assessment.

One of the key characteristics provided by *SoPhy* was the information about weight distribution. Physiotherapists cannot directly observe weight distribution in video consultations. Hence, seeing weight distribution not only between the feet but also across each foot provided crucial novel information. Information about foot orientation and range of movement was also considered useful, but mainly to confirm observations made through the video. Weight distribution, on the other hand, constitutes novel information offered by a wearable technology that is not available in standard video consultations, nor in any related work on technologies for physiotherapists [17,28,37].

While these results are promising, we also identified different challenges in integrating *SoPhy* with clinical practices and tools. Below we offer three design considerations to address these challenges.

Spatial Alignment between Visualisation and Video

We found that although participants appreciated the support by *SoPhy* to get more confidence on their assessment, they found it challenging to comprehend the information along with the ongoing consultation. They found it challenging to map the information of web-interface with the patient's movements, as the interface does not provide any reference point. As a result, understanding dynamic movements like walking was found challenging, as it requires checking information at both screens simultaneously. Participants also described the problem of split attention where looking at the web-interface made them feel being ignorant or rude to the patient. However, as clinicians are effectively using screens during face-to-face consultations [8], managing two screens during video consultations might not be a major issue with repeated exposure to *SoPhy*.

More research is required to present the data such that the physiotherapists can easily incorporate the visualisation as part of their assessment. One possible approach could be to overlay the information on top of the video such that the required information is presented alongside the respective body part. However, it may grab continuous attention from clinicians even at times when they want to focus only on the video stream – which may not be the case when the visualisation is presented on a separate screen as clinicians can ignore it whenever required.

Additionally, instead of presenting all the data at every time to clinicians, we can also present selective information to clinicians based on their needs. For instance, the system could only present the unexpected patterns such as sudden change (peaks or lows) in the weight distribution or range of movement. In this regard, audio and tactile feedback could offer significant potential as these media have been used in the past to effectively present the data [33,41]. Also, as clinicians refer to different bodily cues across different phases of the consultation [3], the web-interface can also be customized accordingly.

Align Visualisation with Clinical Practice

We found issues with the representation of the range of movement, as the provided information did not match with the clinical practice. Physiotherapists measure the range as angular movements of the joints using a device called, Goniometer, whereas *SoPhy* presented this information as a value between 0-10. On the other hand, the representation of weight distribution was substantially appreciated. Participants appreciated the use of different colors, numbers and the foot sketch showing the feet from underneath. Since the information related to weight distribution was new for participants, the presented information did not contradict with their prior clinical knowledge. This highlights that either the information presented by the technology should confirm with the underlying knowledge of the clinicians or it should set new defaults. The new representation may however, involve a learning curve in order for clinicians to embrace the information as part of their clinical practice.

An important aspect of a sensing technology is calibration [19]. *SoPhy* web-interface also needs to be calibrated for different patients as the weight distribution and range of movement will vary for different people. For instance, if the weight scale of 0-30 is calibrated for a person weighing 60 kilograms, it will not show the dark red color for a person weighing 40 kilograms. On the other hand, calibration can be provided to clinicians as a functionality to integrate into therapy. They can adjust the scale of range of movement, for example, as a goal that the patient should achieve in two weeks time.

Reveal Body Structure with Wearable technology

Our study also revealed some of challenges in designing the right socks for physiotherapy assessment. For example, being a wearable technology, *SoPhy* socks restricted participants' ability to visually assess the patient's foot. The loose fitting of *SoPhy* socks also concealed the foot contours and foot arch that participants wanted to observe from the video stream. This issue became more prevalent for extreme pain profiles with toe injury, where visual examination of the barefoot was critical for the assessment.

SoPhy socks need to be designed depending upon the clinical conditions. For instance, for patients with toe injuries, 5-toed socks or toeless socks might be a good design as physiotherapists can see weight bearing for each toe. Another important factor to be considered would be the type of material used for *SoPhy* socks. A body fitting socks made up of a stretch fabric like spandex could be utilized to make the foot contours visible. However, such body-fitting material may cause discomfort for certain patients e.g., those having swollen foot.

The third factor is the color of the socks. Using bright-colored socks could make the movements distinguishable even when used in different environments. And finally, the last key factor is the size of socks as one size *SoPhy* will not work for all. Accuracy of sensor readings will depend upon the fitting of the socks on feet. Hence, different size socks need to be designed for different sized foot. Designing *SoPhy* socks for different clinical conditions is increasingly becoming feasible given the advancements in smart textiles like FlexTiles [29].

LIMITATIONS AND FUTURE WORK

We report two main limitations of this work. Firstly, our study participants had no prior experience with video consultations. Thus, their responses might have some novelty effect, and the findings may differ in real world video consultations with experienced physiotherapists. Secondly, the role of patient was enacted by a healthy individual (actor). Although we significantly trained the actor to perform consistently across all study sessions, there might have been some unavoidable human errors in the movement data. Nevertheless, given the aims of this study, this participant cohort was the closest representative of our target population. The study findings have significant implications for the future video consultations systems.

The very idea behind organizing a video consultation is to support patients in situations when making a physical trip to the hospital is not feasible [11,40]. Extreme pain is one such condition where a long travel to visit the physiotherapists might worsen the patient's pain. In such condition, *SoPhy* could be used as a training tool where the clinician can guide the patient on how to start making lower limb movements. Equally, in low pain conditions when the patient has made a significant recovery, *SoPhy* could help them in optimizing their movements by providing the necessary feedback.

Furthermore, as the *SoPhy* socks afford mobility, it could provide more flexibility to clinicians and patients to try out different types of exercises during video consultations. Clinicians can further personalize the therapy program based on the home conditions of the patient, which further adds to the benefits of video consultations. *SoPhy* can support video consultations for a variety of clinical domains like sports rehabilitation, Orthopedics and Geriatric conditions. Considering the benefits of *SoPhy* particularly, in understating weight distribution, it could also have potential during face-to-face consultations where it could be used both as a training and feedback tool. Our future work thus, involves studying the use of *SoPhy* in natural video consultations for physiotherapy.

CONCLUSION

In this paper, we presented a wearable technology *SoPhy*, to enhance the ability of physiotherapists in conducting lower limb assessment in video consultations of physiotherapy. *SoPhy* provides information related to subtle differences in weight distribution, range of foot movement and foot orientation. Through a laboratory evaluation, we found that *SoPhy* increased participants' confidence in assessing the patient, particularly for squats exercise. *SoPhy* offered invaluable insights related to weight distribution that is neither available in standard video consultation nor in traditional face-to-face settings. Through *SoPhy*, we hope to encourage design thinking towards designing novel video consultations systems for physiotherapy.

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REFERENCES

1. Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout https://www.adafruit.com/product/2472
2. Arduino Pro Mini Microcontroller. https://www.arduino.cc/en/Main/ArduinoBoardProMini
3. Deepti Aggarwal, Bernd Ploderer, Frank Vetere, Mark Bradford, and Thuong Hoang. 2016. Doctor, Can You See My Squats?: Understanding Bodily Communication in Video Consultations for Physiotherapy. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (DIS '16). ACM, 1197-1208. DOI: http://dx.doi.org/10.1145/2901790.2901871
4. Deepti Aggarwal, Robyn Garnett, Bernd Ploderer, Frank Vetere, Patricia Eadie, and Bronwyn Joy Davidson. 2015. Understanding Video based Parent Training Intervention for Children with Autism. In *Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction* (OzCHI '15), ACM, 10-19. DOI: https://doi.org/10.1145/2838739.2838770
5. Swamy Ananthanarayan, Miranda Sheh, Alice Chien, Halley Profita, and Katie A. Siek. 2014. Designing wearable interfaces for knee rehabilitation. In *Proceedings of the 8th International Conference on Pervasive Computing Technologies for Healthcare* (PervasiveHealth '14). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, 101-108. DOI=http://dx.doi.org/10.4108/icst.pervasivehealth.2014.254932
6. Mobolaji Ayoade and Lynne Baillie. 2014. A novel knee rehabilitation system for the home. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '14). ACM, 2521-2530. DOI: http://dx.doi.org/10.1145/2556288.2557353
7. Virginia Braun and Victoria Clarke. 2006. Using Thematic Analysis in Psychology. *Qualitative research in psychology* 3, 2(2006), 77-101.
8. Yunan Chen, Victor Ngo, Sidney Harrison, and Victoria Duong. 2011. Unpacking exam-room computing: negotiating computer-use in patient-physician interactions. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, 3343-3352. DOI=http://dx.doi.org/10.1145/1978942.1979438
9. George Demiris, Neil Charness, Elizabeth Krupinski, David Ben-Arieh, Karla Washington, John Wu, and Bonne Farberow. 2010. The Role of Human Factors in Telehealth. *Telemedicine and e-Health*. 16(4): 446-453.
10. Diabetic Pressure Sensing Stockings. https://www.fraunhofer.de/en/press/research-news/2015/may/Pressure-monitoring-stockings-to-prevent-wounds-in-diabetics.html.
11. Sarah Dods, Jill Freyne, Leila Alem, Surya Nepal, Jane Li, and Julian Jang-Jaccard. 2012. Caring for the Last 3%: Telehealth Potential and Broadband Implications for Remote Australia. Canberra: CSIRO. https://publications.csiro.au/rpr/download?pid=csiro:EP129516&dsid=DS3
12. Julie Doyle, Cathy Bailey, Ben Dromey, Cliodhna Ni Scanaill. 2010. BASE – An Interactive Technology Solution to Deliver Balance and Strength Exercises to Older Adults. In *4th International Conference on Pervasive Computing Technologies for Healthcare, PervasiveHealth* 2010, 1-5.
13. Anne G. Ekeland, Alison Bowes, and Signe Flottorp. 2010. Effectiveness of telemedicine: A systematic review of reviews. *International Journal of medical informatics* 2010, 79(11), 736–771.
14. Geraldine Fitzpatrick, and Gunnar Ellingsen. 2013. A review of 25 years of CSCW Research in Healthcare: Contributions, Challenges and Future Agendas. *Computer Supported Cooperative Work (CSCW)*, 22, 4-6, 609-665. http://dx.doi.org/10.1007/s10606-012-9168-0
15. Flexiforce Pressure Sensor https://www.sparkfun.com/products/11207
16. Flex Sensor 2.2" https://www.sparkfun.com/products/10264
17. Thuong N. Hoang, Martin Reinoso, Frank Vetere, and Egemen Tanin. 2016. Onebody: Remote Posture Guidance System using First Person View in Virtual Environment. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (NordiCHI '16). ACM, Article 25 , 10 pages. DOI: https://doi.org/10.1145/2971485.2971521
18. Jun-Da Huang. 2011. Kinerehab: a kinect-based system for physical rehabilitation: a pilot study for young adults with motor disabilities. In *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility* (ASSETS '11). ACM, 319-320. DOI=http://dx.doi.org/10.1145/2049536.2049627
19. Rose Johnson, Nadia Bianchi-Berthouze, Yvonne Rogers, and Janet van der Linden. 2013. Embracing calibration in body sensing: using self-tweaking to enhance ownership and performance. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (UbiComp '13). ACM, New York, NY, USA, 811-820. DOI=http://dx.doi.org/10.1145/2493432.2493457

20. Agnes W. K. Lam, Danniel Varona-Marin, Yeti Li, Mitchell Fergenbaum, and Dana Kulić. 2016. Automated Rehabilitation System: Movement Measurement and Feedback for Patients and Physiotherapists in the Rehabilitation Clinic. *Hum.-Comput. Interact.* 31, 2016, 294-334.

21. Min Kyung Lee, Nathaniel Fruchter, and Laura Dabbish. 2015. Making Decisions From a Distance: The Impact of Technological Mediation on Riskiness and Dehumanization. In *Proceedings of the 18th ACM Conference on Computer Supported Cooperative Work & Social Computing (CSCW '15)*. ACM, 1576-1589. DOI: http://dx.doi.org/10.1145/2675133.2675288

22. Christian Licoppe, and Julien Morel. 2012. Video-in-interaction: "Talking heads" and the multimodal organization of mobile and Skype video calls. *Research on Language & Social Interaction* 2012, 45(4), 399-429. http://dx.doi.org/10.1080/08351813.2012.724996

23. LilyPad Arduino Main Board. https://www.arduino.cc/en/Main/ArduinoBoardLilyPad

24. Rian McGough, Kade Paterson, Elizabeth J. Bradshaw, Adam L. Bryant, and Ross A. Clark. 2012. Improving Lower Limb Weight Distribution Asymmetry During the Squat Using Nintendo Wii Balance Boards and Real-time Feedback. In *Journal of Strength and Conditioning Research* 2012*,* 26(1), 47–52.

25. Sarah Mennicken, Oliver Sack, and Martina Ziefle. 2011. People and a virtual doctor's visit: learning about multiple acceptance aspects of a telemedical scenario. In *Proceedings of the 5th International Conference on Pervasive Computing Technologies for Healthcare, PervasiveHealth*, 2011, 577-584.

26. Edward Alan Miller. 2011. The continuing need to investigate the nature and content of Teleconsultation communication using interaction analysis techniques. *Telemedicine and Telecare*, 17(2): 55-64.

27. Bijan Najafi, Gurtej Grewal, Saman Parvaneh, Robert A Menzies, Talal K Talal, and David G Armstrong. 2013. SmartSox- A Smart Textile to Prevent Diabetic Foot Amputation. https://diabeticfootonline.com/2013/11/18/smartsox-a-smart-textile-to-prevent-diabetic-foot-amputation/

28. Kenton O'Hara, Cecily Morrison, Abigail Sellen, Nadia Bianchi-Berthouze, and Cathy Craig. 2016. Body tracking in healthcare. *Synthesis Lectures on Assistive, Rehabilitative, and Health-Preserving* 5, no. 1 (2016): 1-151.

29.Patrick Parzer, Kathrin Probst, Teo Babic, Christian Rendl, Anita Vogl, Alex Olwal, and Michael Haller. 2016. FlexTiles: A Flexible, Stretchable, Formable, Pressure-Sensitive, Tactile Input Sensor. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (CHI EA '16). ACM, 3754-3757. DOI: http://dx.doi.org/10.1145/2851581.2890253

30.T. G. Russell, P. Buttrum, R. Wootton, and G. A. Jull. 2011. Internet-based outpatient telerehabilitation for patients following total knee arthroplasty: a randomized controlled trial. The *Journal of Bone and Joint Surgery*, 2011, 93(2), 113-120.

31. Marc R. Sarnow, Barry I. Rosenblum, Aristidis Veves, James S. Chrzan, John M. Giurini, Geoffrey M. Habesrshaw. 1994. In-Shoe Foot Pressure Measurements in Diabetic Patients With At-Risk Feet and in Healthy Subjects. In *Diabetes Care*, 17(9), 1002-1006.

32. Sensoria Fitness Socks and Anklets http://www.sensoriafitness.com/

33. Aneesha Singh, Stefano Piana, Davide Pollarolo, Gualtiero Volpe, Giovanna Varni, Ana Tajadura-Jimenez, Amanda CdeC Williams, Antonio Camurri & Nadia Bianchi-Berthouze. 2016. Go-with-the-Flow: Tracking, Analysis and Sonification of Movement and Breathing to Build Confidence in Activity Despite Chronic Pain. *Human Computer Interaction* 2016, 1-49.

34. Sparkfun Bluetooth mate Silver https://www.sparkfun.com/products/12576

35. Duncan Roderick Stevenson. 2011. Tertiary-Level Telehealth: A Media Space Application. *Computer Supported Cooperative Work (CSCW)*, 20: 61-92.

36. M. A. Stewart. 1995. Effective physician-patient communication and health outcomes: a review. *In Journal of Can Med Assoc*.,1423-1433.

37. Richard Tang, Xing-Dong Yang, Scott Bateman, Joaquim Jorge, and Anthony Tang. 2015. Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing System*s, ACM, 4123-4132. DOI:http://doi.acm.org/10.1145/2702123.2702401

38. Ana Tajadura-Jiménez, Maria Basia, Ophelia Deroy, Merle Fairhurst, Nicolai Marquardt, and Nadia Bianchi-Berthouze. 2015. As Light as your Footsteps: Altering Walking Sounds to Change Perceived Body Weight, Emotional State and Gait. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (CHI '15). ACM, 2943-2952. DOI: http://dx.doi.org/10.1145/2702123.2702374

39. G Tao, P S Archambault and M F Levin. 2013. Evaluation of Kinect skeletal tracking in a virtual reality rehabilitation system for upper limb hemiparesis. In *2013 International Conference on Virtual Rehabilitation (ICVR)*, IEEE, 164-165.

40. Liezl van Dyk. 2014. A review of Telehealth Service Implementation Frameworks. *International journal of environmental research and public health* 11, no. 2 (2014): 1279-1298.

41. Junji Watanabe, Hideyuki Ando, and Taro Maeda. 2005. Shoe-shaped interface for inducing a walking cycle. In *Proceedings of the 2005 international conference on Augmented tele-existence* (ICAT '05). ACM, 30-34. DOI=http://dx.doi.org/10.1145/1152399.1152406

42. Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '11). ACM, New York, NY, USA, 143-146. DOI=http://dx.doi.org/10.1145/1978942.1978963.