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

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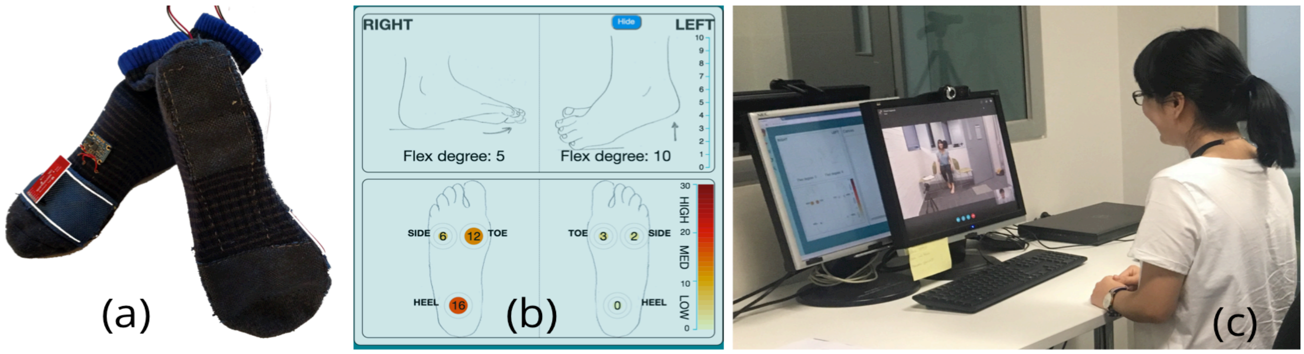

Figure 1: ***SoPhy*** **system: (a) socks with embedded pressure and orientation sensors; (b) web interface displaying information about the range of foot movement and weight distribution; (c) a lab-session of simulated video consultation with** ***SoPhy*****.**

ABSTRACT

While video consultations are increasingly used by physiotherapists, 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 (1) a pair of socks with embedded sensors for patients to wear, and (2) a web interface that displays information about range of foot movement, weight distribution, and foot orientation for physiotherapists in real-time. We simulated 40 video consultations in the laboratory with postgraduate physiotherapy students. We investigated how *SoPhy* enhanced their ability to assess patients as compared to video consultations without *SoPhy*. *SoPhy* increased the confidence in assessing weight-bearing exercises like squats and heel raises. For patients with extreme pain, fewer repetitions were required to make assessment 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 assess, diagnose and treat people with movement problems [12]. Their assessment and diagnosis typically relies on close observations and hands-on work with patients to detect subtle differences in body movement, e.g., a lack of balance while walking or exercising, abnormal distribution of weight in the foot, or limitations in range of movement for different joints [3, 12]. These treatments are typically based on exercises and education to help patients improve their movements and resume their normal lifestyle.

Increasingly, physiotherapists are starting to use video conferencing tools to conduct consultations over a distance [11, 13, 26, 34]. Research on video consultations highlights the difficulties that physiotherapists face in understanding the subtle differences in body movements - which are required to assess patients [3]. Previous work also highlights the importance of clinicians having confidence in their assessment and diagnosis, because the lack of confidence has a negative impact on the patient's trust in treatment [8, 32]. However, there has been little consideration for how to address the challenge of communicating bodily information over a distance to support physiotherapists in their assessments.

This research seeks to address this challenge through a novel wearable technology, *SoPhy,* to capture lower limb movements for physiotherapy video consultations (Figure 1). *SoPhy* consists of (1) a pair of socks for the patient to wear, which contains 3 pressure sensors and 1 Inertial Measurement Unit (IMU) to capture lower body movements, and (2) a web interface that visualizes information about weight distribution, range of foot movement and foot orientation in real-time for the physiotherapist.

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 10 postgraduate physiotherapy students (4 assessments each – 2 with SoPhy and 2 without). The findings highlight that *SoPhy* increased the confidence of participants in assessing weight-bearing exercises like squats and heel raises. For patients with extreme pain, fewer repetitions were required for assessment when using *SoPhy*. For patients with low levels of pain, *SoPhy* helped in comparing the subtle differences in feet movements.

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

Below we discuss the existing literature on video consultations and the existing technology for rehabilitation.

Advancements in Video Consultations

During 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 [11, 13, 26, 34]. During a video consultation, clinician and patient utilize video conferencing tools such as Skype for the purpose of communication. Several works have investigated the potential of video consultations for a number of clinical domains, e.g., surgery [31], physiotherapy [3], Autism parent training [4], and knee rehabilitation [26]. As yet, video consultation systems have been limited to the use of audio and video medium. Stevenson [31] explored the use of multiple screens, and Mennicken et al. [22] utilized interactive wall to enhance the user experience with video consultations.

Recently, Aggarwal et al. [3] challenged the applicability of audio-video medium to offer physiotherapy related consultations. Their study highlighted the difficulty that physiotherapists faced over video in understanding the crucial bodily cues related to patient's body movements. Clinicians could not understand the fine-details related to patient's movements because of the limited visual acuity that video technology offer. The absence of complete information reduced clinician's confidence in suggesting new exercises to patients, and they are limited to tweaking previously recommended exercises in video consultations.

Previous works have emphasized the need to communicate complete information to the clinician, the absence of which influences the treatment outcome and clinician-patient relationship [8, 32]. For instance, the lack of clinician's confidence may reduce patient's trust on the clinician and adherence to the treatment [32]. Furthermore, Lee et al. [19] expressed the fear of dehumanizing clinician-patient relationship with limited ability of clinicians in making decisions over video. While there are evidences that video technology does not support all the essential information that clinicians require [3, 10, 23], lesser attention is paid to explore technologies that could support them in their assessment. We explore the use of wearable technology to enhance clinician's confidence in making assessment.

Technology for Rehabilitation

Within HCI, there is a growing interest in designing systems to support rehabilitation. Previous works have explored different visual feedback strategies to guide patients in the absence of supervised training by physiotherapists. Technologies like Microsoft Xbox Kinect [17] and Nintendo Wii [21] are also investigated to make rehabilitation engaging. However, these technologies do not support the fine-grained movements that are required for assessment in physiotherapy. Additionally, these technologies work best for standing movements. However, the rehabilitation is not limited to static exercises. Patients perform dynamic exercises with different arrangements such as sitting on the chair and lying down on the floor [6].

Recently, Hoang et al. [16] explored the opportunities with virtual reality environment to guide students on body postures for remote sessions. Their proposed system, OneBody requires the users to wear the head mounted displays, which may be suitable for healthy people but might become overwhelming for patients struggling with their health issues. Additionally, the system is mainly designed to correct posture, and not to provide information related to weight distribution or foot orientation. Similarly, other works have also designed technology to support upper limb rehabilitation [25, 33]. For example, Physio@Home [33] designed a system that provides fine-details of upper limb movements such as range arm movements. However, the system cannot be used to capture lower limb movements because of the difference in biomechanics of how different parts of our body works.

Another line of research has been to support lower limb rehabilitation at home. In this regard, PT Viz [5] is a wearable technology that offers feedback to patients undergoing knee rehabilitation by capturing movements through sensors embedded in knee and calf sleeves. Automated Rehabilitation Systems by Lam et al. [18] and Ayode and Baillie [6] utilize sensors to capture patient's movements. The captured data is provided to the physiotherapists to assess patient's recovery. However, these systems are limited to the rehabilitation of knee and hip related injuries. There is far less research on supporting rehabilitation of other parts of lower limbs such as foot and toes. Designing technology for lower limb rehabilitation over video is important because demonstrating lower body movements over video are more challenging. For instance, it requires different camera orientations to capture the required movements, which in turn, may also create privacy concerns when the patient is not aware of the camera view of her body [3].

We explore the use of socks to support physiotherapy related video consultations given the socks have been successfully used in the clinical practice. For instance, previous works have explored the use of interactive socks to support patients with diabetic foot ulcers (e.g., [9, 24]) and to help patients in understanding their postural stability (e.g., Sensoria Fitness Socks [28], sensing shoes [27]). Additionally, as socks conforms to body and moves along with the patient, it has the potential to capture the dynamicity of a physiotherapy related consultation where the patient performs a variety of static and dynamic exercises.

SOPHY

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

Figure 2: The wearable components of *SoPhy:* Each sock consists of three pressure sensors and 1 IMU.

The working of *SoPhy* is as follows. We ask the patient to wear the socks before starting the video consultation with the physiotherapist. During the video consultation, physiotherapist asks the patient to perform different lower body exercises (e.g., squats, and tip toes). As patients perform the prescribed exercises, the socks capture data about weight distribution, foot orientation, and range of foot movements. This data is then sent to the web interface, where the physiotherapist can see this information in real time. We have designed a mobile app to support communication between the socks and web interface.

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 (leg). 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.

We capture this pattern of weight distribution across 2 balls and heel of the foot using pressure sensors sewed on the *SoPhy* socks. Corresponding to each sensor, the web-interface displays numbers as well as a color spectrum on the feet sketches showing the feet from underneath (refer the lower half of Figure 4b). The color spectrum denotes the measure of weight on each point, while the number describes the exact value (in the range of 0 to 30).

Foot Orientation: Foot orientation refers to the alignment of foot in four directions. First is the dorsiflexion, which occurs when the person bears weight on the heel of the foot. Second is the plantarflexion where the weight is on the balls and toes of the foot. Third is the medial orientation where the weight is on the inside of the foot and the person lifts the outside of foot up in the air. And lastly, in the lateral orientation the person bears weight on the outside of the foot and lifts the inside of the foot up in the air. This information is presented on the interface as foot sketches.

Foot orientation is captured by an IMU mounted on the socks at the bridge of the foot. For the web-interface, we used 10 sketches to display the foot orientation: 3 each for dorsiflexion and plantarflexion, and 2 each for medial and lateral orientation. These sketches change on the web-interface based on the captured data. We used sketches instead of the real photographs to represent feet to eliminate gender and age bias. It also improved the latency of updating the web-interface and the readability of the images by removing the background clutter.

Range of Movement: Range of movement refers to the magnitude of foot orientation across four directions described above. The value of each orientation varies between 1 to 10.

DESIGN PROCESS

The final design of SoPhy and its interface were the results of multiple explorations, development and e-sewing trials that spanned over 6 months. We held three focus group discussions amongst us as well as with participants from the community surrounding our research lab. These participants were from different academic backgrounds, e.g., Electrical Engineering, Computer Science, and Interaction Design. Their expertise helped us in refining our design choices in terms of electronics, aesthetics, and wearability. Besides, we also organized multiple meetings with a senior physiotherapist at the collaborating hospital, who offered us knowledge on the foot joint structure and validated our design explorations. Due to the space limitation, we only discuss the key decisions made to reach the final design.

The first thing we explored was identifying the right sensors and microcontroller for capturing the required data. We selected Flexiforce Pressure Sensor [14], 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 (Refer Figure 3a). However, initial testing gave inconsistent results. Moreover, given the small surface area of each toe, sewing five pressure sensors and avoiding short-circuiting was a big challenge. We tried reducing the number of sensors and finally settled with three sensors: one on each ball and one on the heel because we bear more weight in these three areas (refer Figure 2 for the final design).

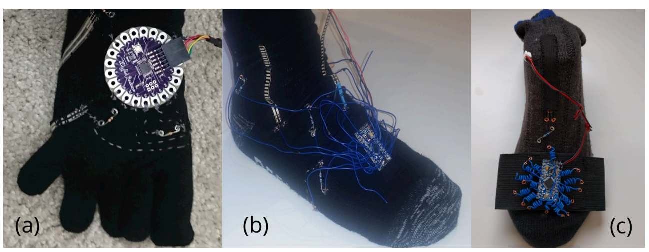

Figure 3: Early iterations of *SoPhy*: (a) Toe socks (b) normal socks with 4 flex sensors (c) normal socks with 1 flex sensor.

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 [15], considering its small size and light-weight. We tested 4 flex sensors by sewing them on socks around the ankle (Refer Figure 3b). Owing to the limited degree of freedom we have around our ankle, this arrangement captured only limited values of the movements. Hence, we discarded flex sensor and opted for a Inertial Measurement Unit. We went with Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout [1], which gave us reliable data on movements.

We also tried two microcontrollers, LilyPad [20] and Arduino ProMini [2] to capture the data from the sensor. After initial testing, we opted for Arduino ProMini, which is smaller in size and has more analog pins to wire in sensors. We finally chose Bluetooth Shield (Sparkfun Bluetooth mate Silver [30]) to transmit captured sensor data to *SoPhy* interface. The selection of hardware in turn also affected the choice of socks as well as the resulted web-interface. As a result, instead of five toe socks, we finally went with the regular socks as shown in Figure 2.

For the web interface, we explored different ways to communicate the movements of foot. Initially, we planned to use real photographs but later settled on sketches to improve latency and readability of movements. We drew sketches that capture the front view of the foot (Figure 4a), but later switched to the side view (Figure 4b) as a typical video call already provides the front view of the patient's foot. The other change for the web-interface was the use of a color spectrum to maintain visual consistency. The final web interface for the *SoPhy* is shown in Figure 4b.

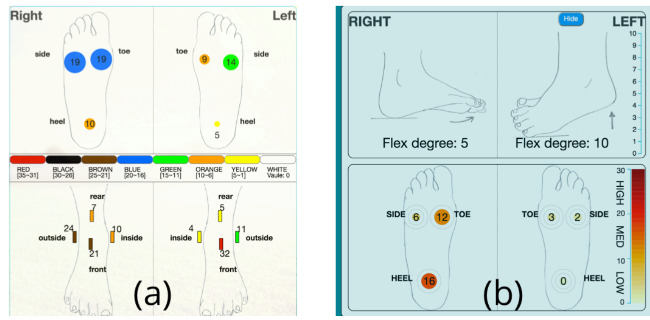

Figure 4: Visualization interface: (a) previous interface with flex sensors; (b) current interface with orientation sensors

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 [19,31], we created simulated video consultation settings to evaluate *SoPhy*. With simulated video sessions, we aimed to mimic the social and technical structure of video consultations as closely as possible. We organized the consultation across two rooms in the lab, using Skype for video conferencing, which is one of the standard tools at the collaborating hospital. We created four patient personas to simulate real life patients. The study was approved by the university ethics committee. This work was conducted in collaboration with a senior physiotherapist (last author) working at a reputed children's hospital.

Participants

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

For the physiotherapist role, we recruited 10 students (3 male, age range: 23-28 years) from second year and final year in 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. Our study participants, as a part of their degree program, had previous experiences in role-playing different patient personas to understand patient's issues and to arrive at a treatment. Additionally, they had completed 37 weeks of clinical practice at hospitals where they assist physiotherapists in treating patients. We utilized their skills

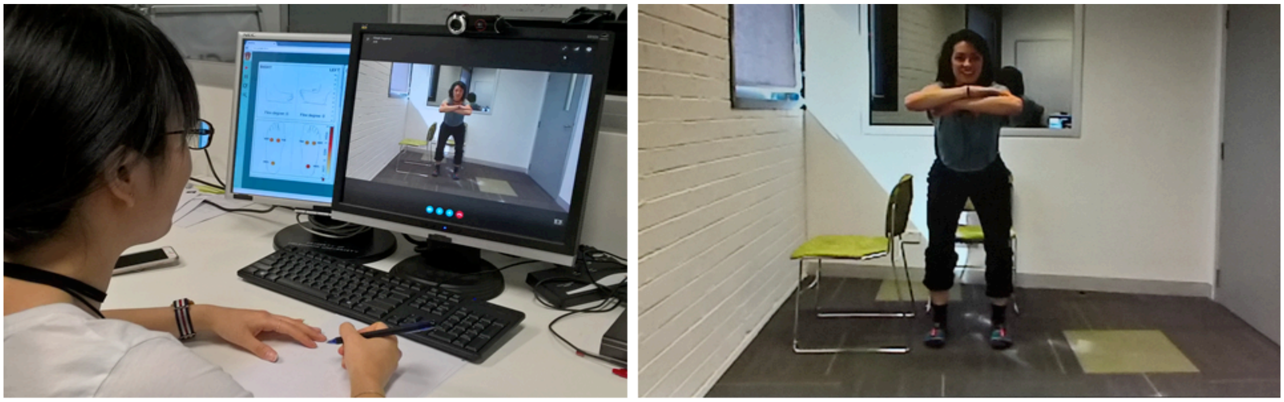

Figure 5: Study setup- In left, a participant using *SoPhy* interface during a video session; Right: patient is performing squats wearing *SoPhy* socks.

to evaluate the utility of *SoPhy* to play the role of physiotherapists in the laboratory evaluation. No participant had prior experience with video consultation or any other wearable technology. The participants received a $20 gift voucher.

For the patient role, we hired a final year physiotherapy student to play the role of patient for the entire study (female, 28 years old) to provide consistency (in line with the earlier study [16]). We refer to the patient role as the actor to avoid any confusion with our participants. We appointed her as our candidate because of her significant 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

For the evaluation, we compared SoPhy against a standard video consultation. The study had two conditions: video consultations with *SoPhy* (SVC) as the test condition, and standard video consultations (VC) without the usage of SoPhy as the baseline condition. The actor and the participants were located in 2 different rooms. In VC condition, communication was conducted through a Skype video call. In SVC condition, in addition to the Skype video call, the participants were presented with the visualization interface of *SoPhy.* Figure 5 shows the study setup.

Independent Variables

The independent variables are the methods of consultations and the patient profiles. There are two methods of video consultations using SoPhy (SVC) and not using SoPhy (VC). There are two patient profiles, extreme pain (EP) and low pain (LP). Based on the independent variables, we designed a 2x2 within subject study. Each participant performed 4 consultations using a combination of two methods each with 2 patient profiles: SVC-EP, SVC-LP, VC-EP, and VC-LP.

Dependent Variables

For each consultation, we asked the participants to evaluate 5 different exercises. For each exercise, the participants filled out a Patient Assessment Form with the following factors: *weigh distribution, foot alignment, range of movement,* and *confidence.* Those factors are the dependent variables of the study and are described in details in the Data Collection section below.

Tasks Performed by the Participants

Each participant was asked to conduct 4 consultations: 2 each for SVC and VC conditions. 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 6 movements (5 exercises and walking) and then filled out the Patient Assessment Form (discussed in the next section). After four sessions, we interviewed the participant to understand their overall experience with *SoPhy.* Each session lasted 2 hours.

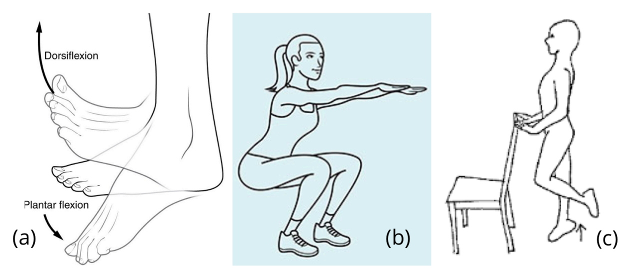

Figure 6: Description of exercises: (a) Dorsiflexion and Plantarflexion, (b) Squats (c) Single foot heel raises.

Tasks Performed by the Actor

The actor was instructed to perform the following 6 movements based on the patient persona: dorsiflexion, plantar flexion, double leg squats, double leg heel raises, single leg heel raises, and walking. Out of these 6 exercises, dorsi flexion 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 the senior physiotherapist (last author) as these exercises were not physically demanding for the actor to perform repeatedly yet they represent the clinical practice to evaluate *SoPhy*.

Patient Personas

Because each participant conducted 4 consultations, we created 4 separate patient personas so that the participant would treat every patient as unique, without any learning effect. The 4 personas were created from two pain profiles: extreme pain and low pain, which were created in consultation with the last author. Table 1 illustrates the names for each persona 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 persona was randomized.

Pain Profile	SVC	VC
Extreme pain	Sam	Veena
Low pain	Susan	Vicky

Table 1: We created 4 patient personas, 2 each for SVC and VC conditions based on two patient profiles.

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. We describe the two patient profiles of extreme pain as an example.

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.

Figure 7: Details of two patient profiles corresponding to the profile of extreme pain.

For these two personas, 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). In the last 2 months, the patient has had 5 face-to-face consultations with the physiotherapist.

For all patient profiles, these video sessions were described as follow-up of face-to-face consultations. Also, all patients were described as already following on the 5 exercises from the last consultation along with the number of repetitions. Therefore, the participants were not required to explain these exercises to patients 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 [29, 33], we employed a mixed method approach where we collected from four sources. Firstly, we video-recorded the laboratory session and conducted participant observations to understand their interactions with *SoPhy*. Being present with the participants allowed us to reflect upon the latest event in a think-aloud manner. Additionally, participants also filled in the Patient Assessment form during each session, which we discuss below. Finally, we also 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 our data collection. We took inspiration from the assessment form of the collaborating hospital and changed it as per the study goals by consulting the last author. Each participant filled in the Patient Assessment Form in each video session.

The form starts by providing background information of the patient (refer Figure 7), and asks 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 gave a starting point to participants to initiate the consultation process.

For each exercise, the participants were required 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, the participant 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 is a self-rated value with labels: lowest, medium, and highest.

The final part of the form is dedicated to write notes related to the overall body posture of the patient and an overall confidence value.

Data Analysis

We performed paired t-test analysis on the following factors between the SVC and VC conditions for the extreme pain and low pain patient profile: weight distribution, foot alignment, range of movement, and confidence assessment. The analysis helps us to determine if the usage of SoPhy would affect the decision making process of the physiotherapists.

We performed thematic analysis [7] on the field notes and interview transcripts. We went through multiple rounds of coding to generate consistent codes. The first author coded the data on paper, and created memos to capture ideas and trends emerging from the data about the interactions with *SoPhy*. The second author performed the quantitative and qualitative analysis on the video recordings where she counted on the number of repetitions performed by the patient in each session. In the second iteration, the first and second author worked together to refine themes for inter-code reliability. Later, all the authors worked together on the emerging themes. Using affinity diagrams, we structure key ideas into four themes that we discuss next.

FINDINGS

Below we discuss the findings across four 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* (SVC) than standard video consultation (VC). For confidence ratings, there was a significant difference in the overall ratings between SVC and VC ($p=0.043<0.05$). *SoPhy* increased the confidence of participants in their assessment (mean 5.25, SD 0.78), as compared to the standard video consultations (mean 4.55, SD 1.6).

The qualitative data showed that *SoPhy* was critical to confirm initial observations made through the video data. All participants conducted their initial assessment based on video information only. Then they verified their observations with the information provided by *SoPhy*: "*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 by patients and the ambiguity created by such dialogue. While participants sought verbal confirmation for their assessment in the VC condition, 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 felt more confident in their assessment with *SoPhy*. This removed the need for dialogue 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."*

Pain profile	Factor	Exercise	*p*	SVC $\bar{x}$ (σ)	VC $\bar{x}$ (σ)
Extreme	Rep.	Dorsi	0.018	7.3 (2.4)	10 (4.42)
	Rep.	Plantar	0.003	6.7 (3.74)	10.4 (4.06)
	Conf.	Squats	0.04	4.75 (0.98)	3.95 (1.03)
Low	Rep.	Dorsi	0.01	8.9 (3.75)	12.9 (4.41)
	Rep.	Plantar	0.03	8.2 (4.08)	10.8 (4.64)
	Conf.	Squats	0.005	5.8 (0.91)	4.4 (0.91)
Overall	Conf.	Overall	0.04	5.25 (0.78)	4.1 (1.72)

Table 2: Statistical Results: p values, mean and SD for confidence (conf.) and repetition (rep.).

Fewer Exercise Repetitions Required to Assess Patients

The participants reported that with *SoPhy* they needed fewer repetitions of each exercise to assess patients compared with the standard video consultation. The quantitative analysis of the video observations showed that there were significant differences in the number of exercise repetitions for both extreme and low pain profile between SVC and VC conditions for dorsi and plantar flexion exercises (see Table 2). SVC required significantly fewer exercise repetitions than VC condition, from 30-50%.

In terms of exercises, there is a significant difference between SVC and VC conditions in rating the confidence for squats for both extreme and low pain profiles.

One reason for the reduced number of repetitions was the increase in confidence in patient assessment with *SoPhy*. The qualitative data showed that 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 zoom in on different body parts, or to position the camera differently to show movement from the front or the side, *SoPhy* provided an additional perspective to the consultation that provided missing information that is difficult to obtain from video signals. "*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 particularly important for patients with extreme pain, to avoid movements that inflict further pain on the patient. "*If a person is in extreme pain, I wouldn't really ask them to do more exercise... I wouldn't want them 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 between consultations and are difficult to observe via 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 the fine-details of weight distribution across each foot. "*It's always challenging to understand the weight distribution. The pressure points are not visible directly, so 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 gave participants insights into the lateral and medial orientation of foot, which are challenging to eyeball. One participant described the difficulty that she faced in checking the lateral and medial 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 are significant differences between SVC and VC conditions in assessing the lateral and medial alignment of the affected foot for squats ($p=0.01<0.05$), double ($p=0.03<0.05$) and single leg heel raises ($p=0.02<0.05$) for extreme pain patient profiles. It is important to note that the result does not indicate the assessment being more accurate, as there is no benchmark available for comparison. However, the difference in the assessment highlights that *SoPhy* does not merely confirm assessments made via video but that it provides a different way to assess the weight distribution across different foot orientations.

Weight distribution information is particularly important to assess weight bearing exercises like squats, double and single leg heel raises, walking and standing posture. As described by the participant: "*I think the socks data will work for all sorts of exercises but it would be more valuable with weight bearing exercises like squats, heel raises. These exercises are less obvious to eyeball. Any closed circuit where your foot is on the ground and you need to manage your weight would benefit from the data.*" (P8)

Participants highlighted that *SoPhy* could be beneficial even in face-to-face consultations to assess the weight distribution of the patient in different exercises: "*The system also has significant benefits in face-to-face setting for weight bearing exercises as they are always difficult to observe. So much is going on at the same time like the full body orientation, how are the knees placed, how about the hip placement, is patient putting equal weight on both foot, and even on one foot where are they putting maximum of their weight. This is a strong tool to guide me how the patient is bearing their weight."* (P6)

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 presented by *SoPhy* with the movements visible through the video. 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 difficult. Participants hence desired that the visualisation would be superimposed on the video so that they could directly relate numbers to movements for each leg. "*If all the information is on the same screen, like information of right foot is closer to the right foot and same for the left foot – without compromising the video size, that would very handy.*" (P4)

Mapping values presented by *SoPhy* with values generally used to assess patients constituted another challenge. In particular, the presentation of the range of movement was found to be confusing, because *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 provided new information, it also concealed information about the foot structure that participants could observe in the standard video consultation (VC) when the sock was not worn. "*The biggest issue with socks 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 may be 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 lower limb movement information. Firstly, participants felt more confident in their assessments when using *SoPhy* compared to standard video consultations. Increasing confidence in assessments is crucial because it impacts consecutive diagnosis and treatment. Furthermore, confidence in assessment is also critical for the clinician's perception by the patient. Lack of confidence can negatively affect the patient's trust in their diagnosis and their adherence to the treatment [32]. Secondly, participants found *SoPhy* particularly useful in assessing patients with extreme pain, because they could assess patients with fewer repetitions than in standard video consultations and thereby reduce the discomfort experienced by the patient.

The key information provided by *SoPhy* was weight distribution. Physiotherapists cannot directly observe weight distribution through 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 only 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.

While these results are promising, we also identified various challenges in integrating *SoPhy* with clinical practices and tools. Hence, the following section offers three design considerations to address these challenges.

Spatial Alignment between Visualization 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. Participants described this behavior as a contradiction to their clinical practice as their focus should always be on the patient. Looking at the web-interface made them feel being ignorant or rude to the patient. Similarly, 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. Furthermore, the cognitive efforts of mapping left and right foot of the patient with the visualisation further increased the complexity.

As such, although all the information presented on the interface was crucial and sufficient for participants to make their assessment, the presentation made it challenging for them to quickly grasp it. More research is, therefore, required to represent the data such that the physiotherapists can easily understand the key bodily information. One effective approach could be to overlay the information on top of the video such that the required information is presented alongside the respective body part. Figure 8 shows a mock interface where the video is augmented with the information required to assess squats. Additionally, more thoughts are required to understand what data should be presented to physiotherapists and when should it be presented. For instance, instead of presenting every data to the physiotherapist, 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 they have been used in the past to present data effectively [29, 35].

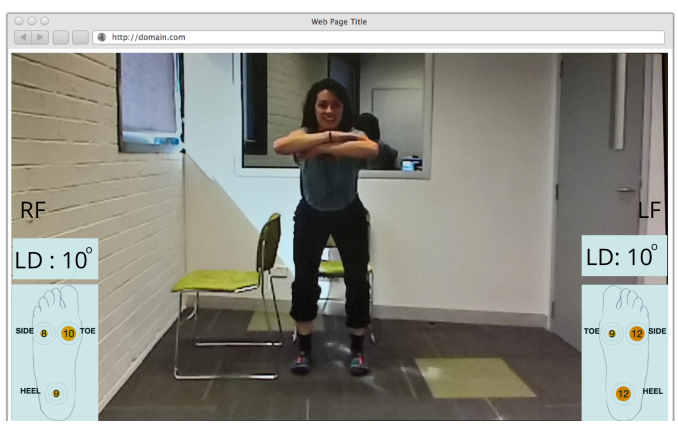

Figure 8: Overlaying visualisation data on the video stream would require less cognitive efforts in mapping.

Align Visualization with Values Used in Clinical Practice

We found issues with the representation of the range of movements 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. The information related to range of movement provided as flexion degree was considered confusing and less meaningful by the participants. The confusion around range of movement influenced participants' understanding of the degree to which the foot has oriented for a particular movement. For instance, although participants got information related to the medial and lateral foot orientations from the weight distribution values, they could not understand the degree of these orientations. Similarly, while participants learnt about the foot in plantarflexion and dorsiflexion position directly from the video, as it is comparatively easier to eyeball, they did not understand the degree of these orientations.

On the other hand, the representation of weight distribution was considerably appreciated. Participants appreciated the use of different colors, numbers and the foot sketch showing the feet from underneath. They valued the information to understand the subtle differences in the pattern of weight distribution across each foot. Since the information related to weight distribution was new for the participants, the presented information did not contradict with their prior clinical knowledge. This highlights that either the information presented by the technology should confirm the underlying knowledge of the clinicians or it should set new defaults if the information is new to their practice. However, the new representation may involve a learning curve in order for clinicians to embrace the information as part of their clinical practice. Longitudinal studies would be required to understand how clinicians adopt the new technology in their routine assessment.

Reveal Body Structure with Wearable technology

Our study also highlighted some issues with the socks when the presence of socks restricted participants to visually assess the patient's foot. For instance, participants wanted to see bodily cues related to the movement of joints, and the arch of the foot. However, participants did not get these details with the designed socks as they were loose fitting socks. Participants suggested having body-fitting sock, made up of a stretch fabric, so that the contours of the foot are visible on top of the socks. Secondly, we also found the relationship of the type of socks and the patient persona. For instance, for profiles with toe injury, participants wanted to see the arrangement of toe, e.g., whether the injured toe is touching the ground or whether it is bearing any weight. To support assessment in such conditions, 5-toed socks might be a good design choice where physiotherapists can see each toe individually.

Additionally, the color of the socks also created an issue where the grey color of the socks blended with the carpet color. This was mainly an issue in extreme pain profile where the range of movements was very less and therefore, participants could not see the actual displacement of foot from the ground. We, therefore, recommend using a bright color like orange for making socks such that the foot movement is easily distinguishable. As such, designers should pay attention towards the color, size and type of the socks while designing a wearable technology.

LIMITATIONS

Our study has certain limitations. Firstly, the study was conducted with participants who had no prior experience with video consultations. Thus, the responses we received might have some novelty effect, and the findings may be different in real video consultations with experienced physiotherapists. Secondly, the role of patient was played by an actor. Although we instructed and trained the patient to be consistent throughout the study sessions, there might have been some unavoidable human errors. 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 design of video consultations systems.

CONCLUSION

In this paper, we presented a wearable technology *SoPhy*, to enhance the ability of physiotherapists in conducting lower limb assessment in video consultations for 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 for both extreme and low pain patient profiles. Participants appreciated the ease and low setup requirement of *SoPhy* to make real-time assessment of weight bearing exercises such as squats and walking.

Wearable technology like *SoPhy* cannot replicate the insights gained through hands-on assessment in face-to-face consultations. However, rather than viewing *SoPhy* as a way to address the gap between hands-on consultation and video consultations, this paper highlighted that the weight distribution information gained by this technology offers a new quality that is neither available in standard video consultation nor in traditional face-to-face settings. We hope that this finding and the lessons learnt from this study will encourage other researchers and designers to follow this path and explore ways of communicating bodily information through wearable technology in ways that empower clinicians and the people they care for.

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