Novel stretch-sensor technology allows quantification of adherence and quality of home-exercises: a validation study

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ABSTRACT
Objective To investigate if a new stretch sensor attached to an elastic exercise band can assist health professionals in evaluating adherence to home exercises. More specifically, the study investigated whether health professionals can differentiate elastic band exercises performed as prescribed, from exercises not performed as prescribed.

Methods 10 participants performed four different shoulder-abduction exercises in two rounds (80 exercise scenarios in total). The scenarios were (1) low contraction speed, full range of motion (0°–90°), (2) high contraction speed, full range of motion (0°–90°), (3) low contraction speed, diminished range of motion (0°–45°) and (4) unsystematic pull of the elastic exercise band. Stretch-sensor readings from each participant were recorded and presented randomly to the raters. Two raters were asked to differentiate between unsystematic pull (scenario 4), from shoulder abduction strength exercises (scenarios 1–3). The next two raters were asked to identify the four different exercise scenarios (scenarios 1–4).

Results The first two raters were able to differentiate between unsystematic pull (scenario 4) from shoulder abduction strength exercises (scenarios 1–3). They made no errors (100% success rate). The second two raters were both able to identify each of the 80 scenarios (scenarios 1–4). They too made no errors (100% success rate).

Conclusions The stretch-sensor readings from the elastic exercise band allow health professionals to quantify whether strength-exercises have been performed as prescribed. These findings have great implications for future clinical practice and research where home exercises are the drugs-of-choice, as they enable clinicians and researchers to measure the exact adherence and quality of the prescribed exercises.

INTRODUCTION
Imagine a situation where a patient with shoulder pain returns for the scheduled 8-week follow-up. The patient complains that the shoulder still hurts and that the exercise programme he was prescribed had no effect. As the prescribed exercise programme has been shown to be beneficial in reducing shoulder pain, the obvious clinical question is why the programme did not work? Adherence to home exercise programmes has often been shown to be insufficient, and therefore clinicians will always be in doubt whether the exercises were performed as prescribed.

Adherence to home exercise programmes has been measured in several ways including recall of compliance, self-administered training diaries and video recording. Recall of compliance and self-administered training diaries are both limited by recall bias and the effect of trying to please the healthcare provider. Video recording of exercises is another option; however, it is expensive and limiting as patients are only able to perform the exercises when they are in front of a video camera in their home. Furthermore, technical challenges and the skills of the patient may hinder proper administration and collection of such data. So, each of these methods have some limitations that may result in errors during reporting of adherence. Thus, there is a need for simple and valid measurements of adherence that do not require self-reported data, are inexpensive and are not based on equipment that relies on the technical abilities of the individual patient.

In studies evaluating the efficacy of pharmacological treatment, it is often possible to use biomarkers in urine or blood as indicators of adherence. This is, however, not possible when the drug-of-choice is specific exercises. In physical medicine and rehabilitation, home-based, unsupervised exercise programmes—such as strength training using elastic exercise bands—are often used after a thorough initial instruction by the prescribing doctor or physiotherapist. Elastic exercise bands have several qualities that make them preferable in rehabilitation. They are easy and safe to use, they provide adjustable resistance, are cheap for the patient to buy and have shown efficacy in clinical trials on shoulder, neck, knee and hip pains.

The primary aim of the current study was to investigate if a new stretch sensor attached to an elastic exercise band could objectively quantify whether shoulder abdution strength exercises have been performed as prescribed. Specifically, first we wanted to investigate whether medical doctors and physiotherapists would be able to differentiate exercise performed as prescribed from exercises NOT being performed as prescribed based on data from a stretch sensor. Second, we aimed to investigate if specific exercise scenarios with different contraction speeds and range of motion (ROM) could be identified.

METHODS
Design
This was a concurrent validity study that investigated if it were possible for physiotherapists and medical doctors to differentiate between elastic exercise band strength exercises performed as...
prescribed and those NOT performed as prescribed—based on stored data from a built-in stretch sensor attached to the elastic exercise band. Video recordings were used as the gold-standards, and recorded concordantly, to ensure that specific strength exercise scenarios matched the stored data from the stretch sensor.

Participants
Ten healthy volunteers, aged 26–38 years, without upper extremity symptoms, were recruited for the study. All participants provided written informed consent, and the study was approved by the Danish Data Agency.

Raters
A total of four (2×2) raters were used. Two were physiotherapists and two were medical doctors. One physiotherapist and one medical doctor acted as raters for each of the two analyses.

EQUIPMENT
Description of the stretch sensor
The elastic stretch sensor was based on the technology designed by Danfoss PolyPower. It acts as an elastic capacitive material that is stretchable in one direction. It allows us to measure how much the sensor is being stretched (for further detail refer to Kappel et al20). The sensor was attached to the rubber band through two clips that made the sensor easily transferable to other elastic exercise bands (figure 1). The sensor was attached via a USB to a small box that recorded data 200 times per second. The sensor is robust, and the material properties are robust to changes during usage.20 A switch was mounted in the handle of the elastic exercise band, so that the data recording would start whenever the handle was pressed. Before the exercise data were collected, we tested the handle switch by pressing it a total of 100 times. Every time the handle was pressed, the data collection started as intended, and the correct information regarding the date and time of day were stored in the memory card.

Description of the elastic band
The elastic band was a standard blue Thera-Band exercise band, which is commonly used in rehabilitation studies.1 4 17 21 To ensure each strength exercise scenario was performed with the same external resistance—corresponding to a relative load of 12 repetitions maximum (RM)—a line was drawn on the elastic exercise band for each 5 cm of its length. The 12 RM-load was determined prior to data collection, and reflected a load that would typically be prescribed clinically to treat conditions of the shoulder, neck and knee.19 22

THE FOUR STRENGTH EXERCISE SCENARIOS
Based on our clinical experience, we decided to include four different strength exercise scenarios. These were chosen to include relevant variations of shoulder abduction training that are often encountered clinically. The exercises were chosen so that they represented relevant variations concerning ROM, and the speed of contraction. Exercise scenarios 1–3 represented shoulder abduction exercises that could be prescribed specifically in this way by the physician or therapist and exercise scenario 4 represented shoulder abduction exercises that were not performed as prescribed. This was to mimic circumstances where some patients would NOT do their exercises as prescribed, at the instructed speed and ROM. In some circumstances, patients do this intentionally (by cheating), unintentionally (by misunderstanding) or in some cases by just not performing their exercises at all.

The four exercise scenarios were performed in the following way:
- Scenario 1: low contraction speed, full ROM (0–90°) (figure 2). Ten repetitions at 12 RM, loading from 0° abduction to 90° abduction. Three seconds concentric, 2 s pause at 90°s abduction, then 3 s of eccentric movement and 2 s pause at 0° abduction. The 10 repetitions took 1:40 min and time-under-tension was 8 s per repetition. This scenario was designed to represent traditional strength exercises, concordant with the evidence-based recommendations of The American College of Sports Medicine for untrained individuals, regarding muscle actions, contraction velocity and intensity.23
- Scenario 2: high contraction speed, full ROM (0–90°s). Ten repetitions at 12 RM, loading from 0° abduction to 90° abduction. 1 s concentric, 2 s pause at 90°s abduction, then 1 s of eccentric movement and 2 s pause at 0° abduction. The 10 repetitions took 1:00 min and time-under-tension was 4 s per repetition. This scenario was designed to represent more explosive strength exercises.24
- Scenario 3: low contraction speed, diminished ROM (0–45°). Ten repetitions at 12 RM, loading from 0° abduction to 45° abduction. A 1.5 s concentric and 2 s pause at 90° abduction, then 1.5 s of eccentric movement and 2 s pause at 0° abduction. The 10 repetitions took 1:10 min and time-under-tension was 5 s per repetition. This scenario was designed to represent strength exercises where full ROM cannot be obtained, as is often seen in patients with severe shoulder impingement.
- Scenario 4: Unsystematic pulls of the elastic exercise band. Participants where told to pull the elastic exercise band in an unsystematic way. They were not told for how long, but only to stop when the investigator told them to. The unsystematic pull was performed for either: 1:40, 1:25, 1:10 or 1:00 min to make the duration resemble that of scenarios 1–3. This scenario was designed to represent strength exercises NOT performed as prescribed.

All participants performed two rounds of the four exercise scenarios, in a randomised order. The exercise scenarios were randomised in blocks of eight. All exercise scenarios were video recorded to ensure it would be possible to compare the data files from the stretch sensor to a gold-standard. Data from all exercise scenarios were correctly stored in the memory card with the corresponding date and time of day.
Before the data collection, each participant was instructed as to how to perform the strength exercise with prescribed speed and ROM for each scenario. A video recording was played during the execution of each scenario. The video recording showed a man performing the exercise scenario in question at the prescribed speed and ROM. The investigator was also allowed to give verbal cues during performance if speed or ROM was not as prescribed. Between each scenario, participants had a 2 min break. Before data analysis, all files were manually compared to the video recordings to ensure that no errors were to be found in the data recordings.

RATING OF THE TRAINING SCENARIOS

When using the current elastic exercise band technology in a future clinical setting, a medical doctor or physiotherapist would initially instruct the patient to obtain the correct exercise form and technique. When achieved, an elastic exercise band recording would be made to constitute a correct template for subsequent validation of the unsupervised home-exercise performed by the patient. At a follow-up some weeks later, where programme adjustments would be made, the prescribing medical doctor or physiotherapist could then use the initial template to quantify adherence to and quality of the home exercise sessions.

Before rating the scenarios, each of the four raters underwent a 15 min training session to allow for familiarisation with the four different exercise scenarios. The raters were told that the amplitude (the height of the signal, y-axis) shows the ROM, with higher amplitude showing higher ROM (figure 3). The x-axis shows the time and the steepness of the signal shows the speed of the exercise, with a steeper signal corresponding to faster ROM. In addition to this information, the raters were shown eight exercise scenarios from two participants who were not recruited into the study.

Analysis 1: differentiation between exercises performed as prescribed from exercises NOT performed as prescribed

This analysis was performed to determine if exercise performed as prescribed (scenarios 1–3) could be separated from exercise NOT performed as prescribed (cheating/misunderstood) (scenario 4).

The first two raters (doctor and physiotherapist) were both, in turn, presented with one of the 80 images on a computer screen. They were told to mark scenarios where exercises were NOT performed as prescribed (scenario 4). The raters were not told how many scenarios existed. The raters did not know each other and all ratings were performed on two separate days.

Analysis 2: identification of specific exercise scenarios

This analysis was performed to determine if different exercise scenarios and qualities could be identified from each other. The second 2 raters (doctor and physiotherapist) were given 5 consecutive repetitions from each of the 4 exercise scenarios from each of the 10 participants. The raters were then presented with four random exercise scenarios from one participant and were asked to mark the four scenarios as either scenario 1, 2, 3 or 4. By using four random exercise scenarios, the raters could not use the method of elimination, as they were presented with scenarios 1, 2, 3 and 4 and had to distinguish between these. The raters did not know each other and rating was done on two separate days.

Figure 2  The four different strength exercise training scenarios, scenarios 1–4 from left to right: scenario 1 (low contraction speed, full range of motion, 0–90°); scenario 2 (fast contraction speed, full range of motion, 0–90°); scenario 3 (low contraction speed, diminished range of motion, 0–45°) and scenario 4 unsystematic pull of the elastic exercise band.

Figure 3  How the signal changes in relation to the stretch of the elastic exercise band is shown.
separate days. All analyses were timed to determine the amount of time it would take to analyse the data.

Data analysis
The \( \kappa \) statistics were used to quantify the degree of correctly identified exercise scenarios from the data files.\(^{25} \)

The sample size was based on the amount of training that a patient usually performs during 8–12 weeks of rehabilitation with 2–3 training sessions per week consisting of three sets of 10 repetitions, corresponding to approximately 80 sets of 10 repetitions totalling 800 repetitions.\(^{26} \)

RESULTS
Analysis 1: differentiation between exercises performed as prescribed from exercises NOT performed as prescribed
Both raters were able to correctly identify exercises performed as prescribed from exercises NOT performed (perfect agreement, \( \kappa \) of 1.00). Rater 1 (physiotherapist) used 3:20 min while rater 2 (doctor) used 4:10 min (table 1).

Analysis 2: identification of specific exercise scenarios
During the review of the 80 exercise scenarios, both raters were able to identify the four different exercise scenarios without making errors (perfect agreement, \( \kappa \) of 1.00, table 2). Rater 3 (physiotherapist) used 12:10 min while rater 4 (medical doctor) used 12:40 min. This time period included loading images onto the computer screen (the 80 scenarios) in a random order of four images per participant per identification round.

DISCUSSION
The aim of the study was to investigate if a new stretch sensor attached to a standard elastic exercise band could assist medical doctors and physiotherapists to determine whether shoulder abduction strength exercises had been performed as prescribed or NOT. The study showed that by analysing stretch sensor readings, a health personnel can precisely determine whether exercises have been performed as prescribed or NOT. Furthermore, the study showed that the four specific exercise scenarios could be identified from each other, with perfect agreement (no errors).

Measuring exercise adherence and quality
We investigated the shoulder abduction exercise resisted by an elastic exercise band, as this exercise alone was recently reported to be effective in reducing neck and shoulder pain in individuals with frequent neck/shoulder pain, by as little a dose as 2 min training daily for 5 weeks.\(^{19} \) When a clinically effective exercise dose is as low as 2 min/day, exercise quality becomes very important for the session to constitute a sufficient exercise stimulus to reduce pain.\(^{19} \) The technology investigated in the current study seems very well suited for such quality monitoring, in addition to being able to quantify training adherence by date and time-of-day registrations. Compared with an exercise diary or video recordings, the technology has the advantage of being fully automatic and training-integrated and requires no additional time or user attention during training.

There may be a number of explanations as to why research investigating the effectiveness of home-based unsupervised exercises might find no effect of exercise.\(^{6} \) The research methodology could be sound, the primary outcome measure reliable and responsive, the patients’ exercise diaries fully completed, and the reported adherence to exercise above 80%. However, researchers will often question whether the self-reported exercise adherence within the exercise diaries is over-reported or the quality of exercises performed has been too low. In physical medicine and rehabilitation, exercise diaries have been used in the last 40 years, and they are a simple estimate of the adherence to home exercises.\(^{25} \) However, the relationship between healthcare provider and patient may cause the patient to over-report the number of training sessions.\(^{13} \) Both over-reporting and under-reporting training sessions causes a threat to the validity of the study, especially when investigating the effect of home-based exercises. The elastic exercise band with a stretch sensor avoids these problems. No data are self-reported and the results of the current study suggest that both doctors and physiotherapists without prior research or academic training can identify the type of training being performed after only 15 min of instructions in the procedure.

Methodological considerations
The current findings are likely to apply to exercises other than the shoulder abduction exercise, but currently it has been investigated for this exercise only. Shoulder rehabilitation can consist of several exercises, for example, shoulder abduction and shoulder internal and external rotation exercises.\(^{1} \) Shoulder rotation exercises cause only a small elongation of the stretch sensor, while shoulder abduction causes larger elongation. Likewise, a strength increase during rehabilitation could cause problems in interpreting the ROM. To continue exercising at a relative intensity of 10 RM, patients will shorten the elastic exercise band, meaning the stretch sensor will be stretched more during exercises. This would show up on the data from the stretch sensor as an increase in amplitude. If patients are seen several times during rehabilitation, this issue can be managed with a new baseline measurement showing the stretch sensor data at the adjusted 10 RM. But even if the order of exercises is unknown, or if patients become stronger, it will always be possible to quantify the number of training session during the period of

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<th>Table 1</th>
<th>Results of analysis 1: exercise adherence</th>
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<td>Rater 2</td>
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The table shows the number of exercises NOT performed as prescribed that raters 1 and 2 successfully identified.

Scenario 1: Low contraction speed, full range of motion (0–90°).
Scenario 2: Fast contraction speed, full range of motion (0–90°).
Scenario 3: Low contraction speed, diminished range of motion (0–45°).
Scenario 4: Unsystematic pull of the elastic exercise band.

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The table shows the number of specific exercise scenarios that raters 1 and 2 successfully identified.

Scenario 1: Low contraction speed, full range of motion (0–90°).
Scenario 2: Fast contraction speed, full range of motion (0–90°).
Scenario 3: Low contraction speed, diminished range of motion (0–45°).
Scenario 4: Unsystematic pull of the elastic exercise band.
rehabilitation including date, time and number of exercise sets per training session.

Clinical implications
Returning to the clinical question posed in the first lines of the introduction: why did the exercise programme not work? Were the exercises performed with inadequate quality or not performed at all? If the participant had been using the stretch sensor attached to their elastic exercise band, the doctor or physiotherapist could quickly have examined their training data and quantified exercise adherence. This would have enabled us to determine if the participant’s lack of results were because of poor adherence, without having to question their recollection or exercise diary.

The recording capacity of the stretch sensor is only limited by the size of the micro-SD card in the data logger. Each training scenario will use up 250 kB of data, meaning that a 2 GB micro-SD card can contain between 3500 and 4000 training sessions, corresponding to several years of training. The only continuous cost of using the equipment is a standard 9 V battery. Each battery will last for approximately 80 training sessions, meaning most patients will not have to change the battery during 3 months of rehabilitation. The cost of the stretch sensor is likely to be comparable with an ultrasound-guided steroid injection which is another treatment option for subacromial impingement in the shoulder.¹

CONCLUSION
The new stretch sensor allows doctors and physiotherapists to objectively measure adherence to specific exercises. Furthermore, specific exercise scenarios with different ranges of motion and contraction speeds can successfully be identified from each other. These findings have great implications for future clinical practice and research, where home exercises are the treatments-of-choice, as they enable clinicians and researchers to measure exact adherence to prescribed exercises and the quality of the exercises being performed.

REFERENCES

Contributors All authors contributed significantly to the conception and design, analysis and interpretation of the data. MSR made the first draft of the article and the other authors helped revise it for its critically important intellectual content. All authors’ approval of the version is to be published. KT is the guarantor. All authors had full access to all of the data (including statistical reports and tables) in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

Competing interests None.

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