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RĪGA STRADIŅŠ UNIVERSITY

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Application of DAid Smart Shirt Technology in Therapy for Patients with Subacromial Pain Syndrome

Summary of the Doctoral Thesis for obtaining a doctoral degree "Doctor of Science (*Ph.D.*)"

Sector – Health and Sports Sciences
Sub-Sector – Sports Medicine and Rehabilitation

Riga, 2022

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The Doctoral Thesis was developed at Rīga Stradiņš University, Latvia

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Abbreviations used in the Thesis

CKCUEST	Closed Kinetic Chain Upper Extremity Stability Test
D	Dominant hand
CT	Computer tomography
DAid	Double Aid
DASH	Disability of arm, shoulder, and hand
ER	External rotation
IR	Internal Rotation
V	Volts
ND	Nondominant hand
NSAD	Non-steroidal anti-inflammatory drugs
n	Number
p	*p* value
ROM	Range of motion
RM	Repetition maximum
s	seconds
SAPS	Subacromial pain syndrome
Sc plane	Scapular plane
SD	Standard deviation
WHO	World Health Organisation

Introduction

Shoulder pain is common in 7 % to 34 % of people of economic age, and 67 % have experienced disability due to shoulder pain at some point in their lives (Luime et al., 2004; Reilingh et al., 2008). Subacromial pain syndrome (SAPS) is one of the common diagnoses that occur in 40 % of general practices (Luime et al., 2004; Juel et al., 2014; Watts et al., 2017).

Subacromial pain syndrome is a functional or dynamic condition, not a static, anatomical phenomenon as it was once defined. It serves as an “umbrella concept” for shoulder joint pathologies such as: degenerative changes in the muscle tendons of the rotator cuff, instability of the shoulder joint, blade dysfunction, and decreased elasticity of the posterior capsule, associated with a set of common symptoms (Diercs et al., 2014).

The ability to control the shoulder blade motion and position is affected in these pathologies, but the motion control in patients with subacromial pain syndrome is very important (Steuri et al., 2017). Physiotherapy, during which the ability to control the shoulder blade is acquired by subjective or objective feedback, is one of the main treatment options for SAPS (Ellenbecker et al., 2010; Diercs et al., 2014; Cools et al., 2014).

Subjective feedback provided to a patient by a physiotherapist is subjective and depends on the physiotherapist's clinical experience and theoretical knowledge as well depends on the ability to present information to the patient clearly and understandably (Lauber and Keller, 2014; O'Keeffe et al. 2016). Objective feedback, such as optical kinematic systems, are complex and unsuitable for use in clinical practice because of the system's technical complexity and the use of additional space in clinical practice (Wang et al., 2017).

The use of wearable technologies in personalized medicine and clinical settings has increased in recent years (Casselman et al., 2017). These technologies allow clinicians to monitor the recovery process and the suitability of therapy in real-time (Dijkstra et al., 2020). Smart textile clothing is one of the most topical innovations in the field of wearable technologies due to its advantages, such as ease of use and cost-effectiveness, compared to other wearable technologies (Eizentals et al., 2020).

The Double Aid or DAid smart textile shirt system for upper limb movement monitoring is part of the DAid smart textile clothing collection, which also includes smart textile socks for gait analysis and smart shirts for chest excursion monitoring. The collection was developed at Riga Technical University within the framework of the European Regional Development Fund project "Smart textile systems for medicine and sports" (No 1.1.1.2/VIAA/1/16/153).

In the framework of the Doctoral Theses, a DAid smart textile shirt prototype was developed, the reliability and validity of its measurements were tested, and the effect of applying the DAid smart shirt prototype as feedback in physiotherapy on the results of functional tests and self-reported measurement in patients with subacromial pain syndrome was studied. Thus, the work was divided into two stages of the Technology Transfer Management process. Phase 1: Analysing and validating technology feasibility, and Phase 2: Developing and demonstrating a prototype of the DAid smart shirt.

The Doctoral Thesis presents the prototype system of the DAid smart textile shirt, its development process and application in physiotherapy for patients with SAPS, what results could be obtained by using it and what conclusions could be drawn during this work.

Aim of the Thesis

To investigate the effect of the objectified feedback provided by the DAid smart shirt prototype on the functional and self-reported outcomes of physiotherapy in patients with subacromial pain syndrome.

Objective of the Thesis

1. To develop a prototype of the DAid smart shirt that can record the position of the shoulder girdle and can be used as objective feedback during a physiotherapeutic intervention.
2. To evaluate the reliability and validity of DAid smart shirt prototype measurements for recording shoulder girdle displacement as a justification for the use of objective feedback in patients with subacromial pain syndrome.
3. To study the effect of physiotherapeutic interventions with the use of the DAid smart shirt prototype on the functional test and self-reported outcome measurements of patients with subacromial pain syndrome.

Hypotheses of the Thesis

For patients with subacromial pain syndrome, the physiotherapeutic intervention with the use of the DAid smart shirt prototype as objective feedback will achieve equivalent or better functional tests and self-reported outcome measurement results compared to conventional methods.

Novelty of the Thesis

The DAid smart textile shirt prototype developed within the framework of the Doctoral Theses is practically applied in the clinical practice, its impact on the clinical result is evaluated, as well as the use of DAid smart textile prototype in the treatment of patients with subacromial pain syndrome substantiated.

1 Materials and methods

1.1 Conceptual framework of the study

The DAid smart shirt prototype was developed following the guidelines for the Technology Transition Management Process developed by the United States Government Accountability Office (GAO), shown in Figure 1.1 (Sullivan et al., 2015).

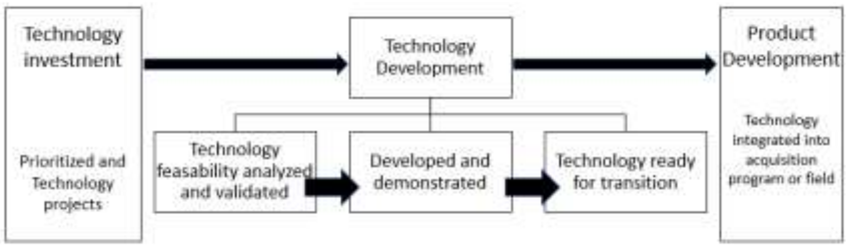

Figure 1.1 **Technology Transition Management Process** (Sullivan et al., 2015)

The technology transition management process is initiated by investing in technology development. At this stage, technical objectives are clearly defined, agreements between stakeholders are secured, technical specifications and expected options, funding requirements, and a development timetable for technological development are set out (Sullivan et al., 2015).

The development of technology consists of three stages:

1. Technology Feasibility analysis and validation. At this stage, prototypes are created in the laboratories for the technology, and their operation, possibilities, the validity of the application, and measurement are evaluated (*ibid.*).

2. Development and Demonstration. At this stage, technology prototypes are developed and applied in laboratories in non-laboratory settings. The performance of the prototype and the impact of the operation in conditions outside the laboratory that is close to the real environmental conditions in which the technology is intended to be used are evaluated. Feedback from prototype users and development recommendations is received (*ibid.*).
3. Technology ready for the transition. At this stage, the technology is tested in the environment in which the technology is intended to be used. The transition phase marks a gap between the technology behind the technology and the users of the technology, and the gap at this stage hinders the transition of the technology from a prototype to a mature product. (Sullivan et al., 2015).

The last stage of the technology transition management process is the Product Development stage, in which the technology is integrated into the learning programs and the work field – the environment for which the technology development was intended (*ibid.*).

1.2 Structure of the study

The Doctoral Thesis includes two stages of the Technology Transition Management Process. Within the framework of these stages, studies were tailored with the following study designs:

First stage

a. Experimental application of DAid smart shirt prototype in physiotherapy – a case study (Development of a New Method to Monitor Shoulder Girdle Motion for Ballerina with Shoulder

Impingement Syndrome Based on DAid Smart Shirt Application) (Semjonova et al., 2018).

b. The reliability and validity of DAid smart shirt prototype measurements were performed in the study “Assessment of Shoulder Girdle Elevation Motion Using DAid Smart Shirt: A Reliability and Validity Study” (Semjonova et al., 2019).

At this stage, the development of a prototype of a DAid smart shirt capable of recording the position of the shoulder girdle and used as objective feedback for patients with subacromial pain syndrome are sequentially described.

Second stage

a. A randomized controlled trial (Semjonova et al., 2020) was conducted to investigate the effect of the objectified feedback provided by the DAid smart shirt prototype on the functional and self-reported outcomes of physiotherapy in patients with subacromial pain syndrome.
b. Feedback in the form of recommendations has been provided to researchers of Riga Technical University the Institute of Design Technologies and BINI (Institute of Biomedical Engineering and Nanotechnology) on the technical development of a prototype DAid smart shirt according to the needs of physiotherapy in work with SAPS patients.
c. At this stage, a prototype of the DAid smart shirt in a clinical setting was investigated through physiotherapeutic interventions, as well as the effects on the performance of patients with SAPS using functional tests and self-reported measurement results.

1.3 Participants in the study and adherence to ethical principles

Participants in the first stage

A clinical case study participant was a woman, aged 24 years, a professional ballet dancer (14 years of experience in the art of ballet) with a BMI of 19.3. Ultrasonographic description: subacromial pain syndrome, no signs of tendon rupture. History of the main complaint: inability to keep the right shoulder line in line with the left shoulder girdle due to pain and shoulder instability. Symptoms have appeared in the last week. There are no reports of acute injury or changes in routine training.

The study was conducted following the Declaration of Helsinki, and the study protocol was approved for execution by the Ethics Commission of Riga Stradins University (No 4/05.10.2017). Before participating in the study, the study participant gave oral and written consent to participate in the study.

Twenty-two volunteers aged 24.2 (SN 3.3) with a body mass index of 19.3 (SN 0.5) were enrolled in a study on the reliability and validity of DAid smart shirt prototype measurements. Before the study, participants gave oral and written consent to participate in the study. The study was conducted following the Declaration of Helsinki and was approved by the Ethics Commission of Rīga Stradiņš University (Opinion No 183/26.01.2017). Each study participant was informed about the process of the study and the data processing in an information letter.

Participants in the second stage

In a randomized controlled trial, participants were divided into a DAid smart shirt group and a control group. A total of 34 participants with a diagnosis of subacromial pain syndrome were included in the study.

Patient selection and randomization in the study

The randomization of patients in the study was as follows:

1. The process of the study was reported to the doctors working at the "ORTO Clinic", who referred the patients for rehabilitation.
2. Patients diagnosed with subacromial pain syndrome were registered with the administration of "ORTO Clinic" to receive rehabilitation / physiotherapy services.
3. The administrator of "ORTO Clinic" made a patient record in the work schedule.
4. At the same time, a list of patients was created in an Excel program file, which was not available to the "ORTO Clinic" administration. From this list, each even-numbered patient who enrolled was assigned to the study group, and each odd-numbered patient was assigned to the control group.

Criteria for inclusion and exclusion of patients

The inclusion criteria were:

- Non-traumatic shoulder problems that cause pain, localized around the acromion;
- Clinically set SAPS diagnosis by an experienced orthopaedic specialist;
- Ultrasound or MRI imaging tests with a conclusion by an expert radiologist in shoulder pathology:
- subacromial impingement sign, subacromial pain syndrome;
- "ORTO Clinic" patients that agreed to participate in the study free of charge;

- At least 3 out of 5 SAPS tests should be positive: Painful arc, Empty can (Jobe test), External rotation resistance test, Hawkins–Kennedy test, Neer test.

The exclusion criteria were:

- Any radiologically verified malignancy;
- Previous fractures in the shoulder complex and / or shoulder surgery on the affected side;
- Osteoarthritis of the glenohumeral joint;
- *Os acromiale* or hooked III type acromion;
- Instability in any joint of the shoulder complex;
- Complete or partial rotator cuff or long head of biceps tendon tears;
- Clinically verified polyarthritis, rheumatoid arthritis, fibromyalgia, frozen shoulder;
- Symptoms from the cervical spine and pseudo paralysis;
- Any systemic or neuromuscular disorder;
- A body mass index (BMI) > 30 kg/m2.

One of the aims of the used exclusion criteria was to create a homogenous test and control groups for decreasing the possible impact of patient individual variations on the results of the study.

An additional reason for the BMI limit was the single-sized smart shirt prototype adopted in the study.

Although the fitness shirt was quite elastic and could be used by people of different shapes, the textile stretch sensors are less sensitive when overstretched.

For the study, 60 participants were selected diagnosed with subacromial pain syndrome. Of the pre-selected participants, 20 participants did not continue the study, of whom 13 did not meet the inclusion criteria, 4 participants refused to participate, and 3 participants had other reasons for not participating in the study.

For randomization in the study and control group, 40 study participants were referred to the inclusion and exclusion criteria, with 20 assigned to the DAid smart shirt group and 20 to the control group. All participants were assigned to the intervention. The results of the intervention were evaluated and analysed for 17 participants in the DAid smart shirt group and 17 participants in the control group.

For the research, the permission of the Ethics Committee of Rīga Stradiņš University No 11/08/08. A protocol for a set of functional tests was developed and approved for use by the Ethics Committee of Rīga Stradiņš University.

The participants of the study were orally informed about the course of the study before the start of the study. Before the study, each study participant signed an informed consent document.

1.4 First stage – materials and methods

1.4.1 Experimental application of DAid smart shirt prototype in physiotherapy

In a clinical case, a prototype of the DAid smart shirt was used experimentally in the context of the clinical environment outside the laboratory. Intervention by experimentally using the DAid smart shirt prototype was the performed movement control tasks for the patient. Tasks were divided into 2 parts:

1. Movement control tasks in which the optimal position of the shoulder girdle in the rest position and the stable position of the shoulder girdle during arm elevation in the frontal, sagittal, and scapular planes were performed.

When the optimal position of the blade was performed, the control of the blade movement during active tasks followed: elevation of the humerus up to 90° in the frontal, sagittal, and scapular planes. The movement was performed 10 times in 2 minutes.

As feedback on the task to be performed, a curve from the prototype of the DAid smart shirt on the computer screen is observed. The study participant then, looking at the computer screen, independently placed the shoulder girdle in the optimal rest position so that the average value of the DAid smart shirt curve does not exceed the threshold: of 0.02 relative units.

2. muscle-specific (m. Trapezius, m. Serratus anterior) tasks.

After 4 weeks, muscle-specific tasks were also initiated (Ellenbecker et al., 2010; Cools et al., 2020), maintaining an optimal shoulder blade position. The participant performed these tasks for the remaining 4 weeks, during which the load was increased, observing the basic principles of muscle strength training:

- Intensity: 60–70 % of 1 RM (repetition maximum) at the start of training therapy, ≥ 80 % at the end of 1 RM in the absence of symptoms. Weight adapted to the patient.
- Dose or amount: 8–12 repetitions for each task in 3–4 sets.
- Frequency: exercises for shoulder girdle muscle groups 2 times a week, with a break of 48–72 h between physiotherapy appointments.
- Progression: a gradual increase in load by changing the following parameters: weight (resistance) and the number of repetitions per set (Allen et al., 2014).

1.4.2 Reliability and validity of DAid smart shirt prototype measurements

As part of the first phase of the technology transition management process, the following study on the reliability and validity of DAid smart shirt prototype measurements was conducted. The method for evaluating objective shoulder girdle displacement was The DAid smart textile shirt system used to evaluate shoulder girdle displacement.

The "gold standard" method to compare the new DAid smart shirt prototype for evaluating shoulder girdle displacement was a two-camera 2D motion recording system (Quintic Biomechanics v26, UK). Four sensors with a reflective surface (diameter: 1 cm) attached to the shirt with adhesive tape were used to record the transfer data. Recording speed – 100 frames / second.

Sensors are located on the right and left *angulus acromialis* (R_AA, L_AA) and *trigonum spinae scapulae* (R_TS, L_TS) at rest according to the recommendations of the International Society of Biomechanics (USA) for the evaluation of biomechanics of upper extremity movements (Wu et al., 2005).

1.4.3 Description of the study intervention for data collection

Participants performed the movements in an upright position with their feet shoulder-width apart, and arms along their sides. When turning on the video and smart shirt prototype recording, participants were instructed: "Raise the right / left shoulder blade as high as possible in three seconds, then lower the shoulder" (right / left elevation and depression) (Bet-Or et al., 2017). This procedure was repeated three times, with a 10-second pause between repetitions. To avoid fatigue, one minute of rest was given between the directions of movement and the sides of the body (Bet-Or et al., 2017). The Metronome Beats application on the Sony Xperia™ smartphone, set at 60 beats per minute, was used to count the seconds. The recording of each measurement lasted 13 seconds.

1.4.4 First stage variable

Relative units of the textile sensor. The feedback is provided by the textile sensors on the screen of the smart device during the execution of the task.

1.5 Second stage – materials and methods

The study "Evaluation of Shoulder Girdle Elevation Displacement Using DAid Smart Shirt Technology: A Reliability and Validity Study" (Semjonova et al., 2019) concluded that the DAid smart shirt prototype measurement results are reliable and valid for estimating the shoulder girdle elevation. Therefore, the transition to the second stage of the technology transition management process was made.

1.5.1 Place of the study

In a randomized controlled trial, participants were divided into the DAid smart shirt group and the control group using the 1: 1 distribution principle. The investigation took place on the premises of SIA "ORTO Klīnika", Āgenskalns branch in the period from January 2019 to March 12, 2020, when an emergency in the country began (Cabinet Order No 103 "On Declaring an Emergency") due to the Covid-19 virus pandemic, as a result of which the practical part of the study was terminated.

1.5.2 Intervention

In the first physiotherapy examination and functional evaluation session, all study participants were required to complete a DASH questionnaire, patient history was collected, and an 8-week session schedule was established for the practical part of the study.

Following evidence-based recommendations (Reinold et al., 2009; Diercs et al., 2014; Klintberg et al., 2015; Pieters et al., 2020), the individual training plan covered 8 weeks, with 2 sessions per week (24–72 h intervals) in the presence of a physiotherapist for 30 minutes.

The training plan consisted of an initial, a basic, and a final phase.

Initial stage of training therapy

In the initial phase, or during the first 4 weeks, movement control tasks were performed (Appendix 1), where the shoulder girdle was controlled while performing shoulder joint flexion, abduction tasks in the frontal, sagittal, and scapular planes (Ellenbecker et al., 2010; Comford & Mottram, 2012; Cools et al., 2020).

The tasks were performed at an individual pace so that the participant could follow the curve on the computer screen (DAid smart shirt group) or provide feedback: visually by looking at a mirror image or in audio from a physiotherapist (control group).

In each plane, the patient performed 10 movements in 3 sets with a 1-minute break between them (Allen et al., 2014).

Before starting the exercise, the physiotherapist manually corrected the position of the shoulder girdle by positioning the shoulder blade according to landmarks: the acromion is above the upper medial corner of the shoulder blade, the medial edge of the shoulder blade and the lower corner fit on the chest (Worsley et al., 2013). The participant was asked to hold the position and repeat it independently, trying several times.

Basic stage of training therapy

Strength and shoulder stabilization tasks specific to the shoulder girdle were performed in the baseline phase (Appendix 2) (Ellenbecker et al., 2010; Cools et al., 2020). The basic principles of the ACSM's Guidelines for Exercise Testing and Prescription (Allen et al., 2014) were used for task progression:

1. Intensity: 60–70 % of 1 RM at the start of training therapy, ≥ 80 % at the end of 1 RM in the absence of symptoms.
2. Dosage or quantity: 8–12 repetitions for each task in 3–4 sets.
3. Frequency: exercises for shoulder girdle muscle groups 2 times a week, with a break of 48–72 hours between sessions.

The tasks were performed under the supervision of a physiotherapist. The participants of the study were recommended to follow the position of the shoulder girdle during daily activities between physiotherapy sessions, but no recommendations were given regarding the performance of exercises independently without the supervision of a physiotherapist.

Intervention for the DAid Smart Shirt Group

In addition to the training therapy intervention procedure described above, the DAid Smart Textile Shirt Technology Prototype Group was provided with detailed guidance on the use of DAid Smart Shirt during physiotherapy tasks. Throughout the intervention period – 8 weeks – DAid smart shirt prototype was used for tasks that had to monitor the stability of the shoulder girdle and the quality of movement performance.

Instructions for using the DAid smart shirt prototype

1. Before performing tasks, turn on the data acquisition unit and open the DAid smart shirt data processing program on the computer, making sure that the data acquisition unit is connected to the computer where the shirt information can be read via Bluetooth.
2. A prototype of a DAid smart shirt should be dressed by attaching a data acquisition unit to the shirt.
3. The data acquisition unit must be switched on.
4. Before performing tasks, make sure that the sensors are in the rest position or the initial position of signal reception, where the value of the curve (relative units) on the screen is close to "0".
5. Following the curves shown on the screen (Appendix 3), the sensors should be placed in the starting position for peace or signal reception.
6. The screen of the smart device should be placed at a height comfortable for the user, without causing compensatory movements of the cervical spine in the direction of flexion, extension, lateroflexion, and rotation.
7. During movement control tasks involving humerus elevations below 90 degrees (arms raised at shoulder girdle) in the frontal, sagittal, and scapular planes, the curve displayed on the screen must be followed during tasks.
8. Muscle strength training tasks performed in a vertical position using medium and submaximal weights should follow the curve displayed on the screen during execution.
9. After completing the tasks, disconnect the data acquisition unit and remove the prototype of the DAid smart shirt.

Final stage of training therapy

In the last physiotherapy session, study participants were required to complete a DASH questionnaire as well as functional clinical tests: shoulder muscle isometric strength tests to obtain an ER/IR ratio of "90/0", "90/90", D (dominant or leading arm), ND (non-dominant hand); CKCUEST. Participants were evaluated according to one standardized functional test set protocol.

1.5.3 Description of second stage variables

1. Upper limb disability, assessed by the patient's self-reported DASH questionnaire, which consists of 30 questions in the basic module, 4 questions in the work module, and 4 questions in the sports module. Answers are given on a Likert scale of 1 (no symptoms) and 5 (maximum symptomatology), where points are obtained according to the questionnaire methodology: "At least 27 out of 30 questions must be answered to calculate the result. The values of the marked questions are added and calculated by dividing by the number of answered questions, subtracting 1, and multiplying the result by 25 to obtain a value in the range of 100 points. A higher score indicates a greater disability." (Franchignoni et al., 2014, Institute for Work & Health, Canada).
2. Upper limb performance assessed by functional test: CKCUEST. The test is performed in the closed kinematic position with activity for 15 seconds with 3 repetitions. The activity includes bilateral arm support and the ability to shift weight from one wrist to another. Weight transfer or touch times or points are positive discrete numbers. The test position in women is modified (Tucci et al., 2014; Cools et al., 2016). The test represents an improvement in function in patients with subacromial pain syndrome after treatment (Tucci et al.,

2014; Tucci et al., 2017). The use of the test before initiating therapy in acute and subacute pain in patients with subacromial pain syndrome is contraindicated (Tucci et al., 2017).

3. Ratio of external (ER) and internal (IR) rotational forces in positions “90/0” and “90/90” (Appendix 4). Where the shoulder joint is in 90° abduction and 0° external rotation, and the shoulder joint is in 90° abduction and 90° external rotation, the isometric force (N) for external rotation (blue arrow) and internal rotation (red arrow) in the direction of resistance is evaluated. Measurements are performed with a handheld portable dynamometer MicroFET®2 (Hoggan Health Industries Inc., Salt Lake City, UT, USA). The ratio is obtained by dividing the external rotational force (N) by the internal rotational force (N) (Cools et al., 2016).

2 Statistical analysis

In the first stage

a. Data were transferred from the FastreaderLabView environment of the data processing and representation software to Microsoft Excel 2016. The time for which stability was maintained in the shoulder girdle and the value of the relative units of the sensor was maintained < 0.02, was expressed in percentage and analysed using descriptive statistical methods: minimum and maximum values.

b. Reliability and validity of DAid smart shirt prototype measurements.

   1. Initially, interpolation of motion video analysis and DAid smart shirt prototype measurements were performed in Microsoft Excel 2016.
   2. To determine the reliability of the DAid smart shirt prototype measurement results, Cronbach's alpha was calculated, and the Interclass Correlation Coefficient (ICC) was calculated to characterize the repeatability, accuracy, and reliability of the test-retest. (< 0.4 – poor, 0.4–0.59 – moderate, 0.6–0.74 – good, > 0.75 – excellent repeatability of measurements) (McGraw et al., 1996). Confidence interval 95 % (95 % CI).
   3. The Bland–Altman method was used to evaluate the validity of the measurement results of the DAid smart shirt prototype, comparing two quantitative measurement methods at a 95 % confidence interval, $p < 0.001$ (Giavarina., 2015).

Statistical reliability was determined at 5 %, and results were considered statistically significant if $p < 0.05$.

In the second stage

To determine the effect of the DAid smart shirt prototype on the functional performance of patients with subacromial pain syndrome, a randomized controlled trial was performed using functional tests and self-reported measurement results. The study data were analysed using the following statistical processing and analysis methods:

1) descriptive statistical methods: determining mean values, standard deviations, minimum, maximum values, and 95 % confidence interval.
2) methods of inferential statistics:
   - The Mann-Whitney U test and the Wilcoxon Signed Ranks test were used to compare results between the study and control groups and before and after treatment.
   - The Chi-square test and Fisher's exact test were used to determine the difference in the frequency of the qualitative variables of the samples (age, gender, dominant (D) hand, sport, profession, adjunctive therapy methods).
   - The Wilcoxon Signed Ranks test (DASH Work Module) and the Student's t-test (DASH and DASH Sports Modules) were used to measure the magnitude of the statistical effect before and after the intervention. Determination of normal distribution by the Shapiro-Wilk test.
   - The Cohen's *d* value was used to estimate the statistical effect (for the DASH and DASH Sports modules), which was divided into four gradations according to closeness: 0.1–0.2 – small; 0.3–0.5 – average; 0.6–0.8 – large; > 0.9 – very large. And the value of the coefficient *r* was used for the DASH working module, where 0–0.3 – small; 0.3–0.5 – average; > 0.5 – large.

Results with a p value of < 0.05 were considered statistically significant. The statistical power of the study was determined to be > 0.8 (80 %).

Data were analysed in Microsoft Excel 2016 (Microsoft Corporation, Washington, USA) and SPSS Statistics V22.0 (IBM Corporation, New York, USA).

3 Results

3.1 First stage

3.1.1 DAid smart shirt prototype

The prototype of the DAid smart shirt has been developed by researchers from the Rīga Stradiņš University in collaboration with researchers from the Institute of Design Technologies and the Institute of Biomedical Engineering and Nanotechnology at Riga Technical University. The prototype of the DAid smart shirt has been developed within the framework of the European Regional Development Fund project "Smart textile systems for medicine and sports", project implementation agreement No: 1.1.1.2/VIAA/1/16/153.

Prototype design of DAid smart shirt

The prototype of the DAid smart textile shirt technology (Figure 3.1) consists of two main parts: knitted textile tensile sensors for motion monitoring (shown by the red arrow in the Figure) and a sports T-shirt with fabric flexibility close to that of the sensor (North Bend©, cycling LS jersey).

Figure 3.1 **Prototype of DAid smart shirt**

The sensors are sewn on a tight-fitting sports T-shirt. Sensors knitted from conductive wires are connected by electrically conductive wires (Shieldex 117/17, Statex Produktions- und Vertriebs GmbH, Bremen, Germany) with low electrical resistance (~ 1 kW/m) (Eizentals et al., 2020).

The sensors are connected to the data acquisition unit or control unit. The data acquisition unit measures the electrical resistance of the sensors at 175 Hz, where information about the deformation of the sensors is transmitted via a Bluetooth connection to the screen of a computer or other smart device, providing the user with immediate feedback on movement (Eizentals et al., 2020).

Characteristics of the sensors used in the DAid smart shirt

The resistance of the sensor varies in proportion to the elongation of the sensor and this property can be used to track human movements through the deformation of clothing. When the sensor is stretched, the change in resistance (signal) starts from 5 % of the change in the original length of the sensor and continues to about 20 % of the change in sensor length.

The electrical resistance increases in proportion to the elongation of the sensor obtained by deforming the wearer's clothing (Eizentals et al., 2020).

Textile sensor data reading

Deformation-related changes in sensor resistance are recorded when the textile sensor is connected to the voltage divider circuit. The output voltage of the divider is converted to a digital signal using a 10-bit analog-to-digital converter (ADC) that can detect 1024 (2 ^ 10) discrete analogue levels (0–1023). ADC converted numbers are sent to the computer via the Bluetooth radio channel (Appendix 5). The obtained ADC numbers are normalized to obtain the device output signal – the normalized sensor voltage. The normalized sensor voltage varies in the range from 0 to 1 in relative units, which corresponds to a change in the real sensor from 0 to 3.3 V (Pelgrom., 2013).

Justification for the location of the DAid smart shirt sensor

In the general context of rehabilitation, the location of the sensor depends on the required application and the target movement to be achieved during the rehabilitation phase, and this is essential to ensure proper movement monitoring (Wang et al., 2017). Improper placement causes sensor malfunctions, inadequate measurements, and additional signal noise from adjacent joints that are not monitored (Eizentals et al., 2020).

For the prototype of the DAid smart textile shirt, the sensor for elevation monitoring is sewn to the shoulder girdle so that the initial attachment is at the level of the armpit in the middle of the respective shoulder girdle (*spinae scapulae* in the middle view from behind). The sensor passes over the shoulder girdle in the direction of the angulus inferior scapulae, where the sensor end mount is located (Appendix 6).

The position, direction, and length of the appropriate sensor are measured and calculated as a result of "trial and error" until the most appropriate position is obtained to read the highest quality and most informative data during shoulder elevation. Shirt adjustment to assess shoulder blade displacement was used by Mokhlespour Esfahani et al. modified methodology (Mokhlespour Esfahani et al., 2017).

The data acquisition unit was placed in the pocket on the back of the elastic shirt (the red circle line in Figure 3.1), thus not interfering with the freedom of movement of the study participant.

DAid smart shirt prototype feedback principle

A person dressed in a prototype of a DAid smart shirt should perform a physiotherapy task / exercise, during which the quality of the task is monitored by looking at the computer screen. The completed task was recorded in real-time (Appendix 7).

The main purpose of the sensors is to inform the user about the movements of the shoulder girdle. When the shoulder is activated, the sensors extend or remain at rest with the clothing on the wearer's back (Semjonova et al., 2018). During appropriate motion control tasks, the sensors should be in a rest position that the user should try to maintain while avoiding an increase in the sensor signal (Eizentals et al., 2020).

The calibration procedure is not performed in the case of the DAid smart shirt prototype, because the initial state of the system user is the position of the "0" curve on the screen for both sensor signals.

DAid smart shirt prototype data processing software

Data were collected from 2 knitted tensile sensors and transferred via Bluetooth transmission system to data processing and representation software "Fastreader" in the LabView environment (author: A.Kataševs, RTU) (Oks et al., 2015; Oks et al., 2016).

The receiver for this work is a laptop with Data Single software, which is designed to work with this module. The software displays changes in the sensor signal in real-time, providing feedback to the user.

3.1.2 Experimental application of DAid smart shirt prototype in physiotherapy

Data from a prototype of DAid smart shirt showed that during physiotherapy intervention, where the DAid smart shirt prototype where used, right shoulder girdle stability time increased during movement control tasks: in the sagittal plane, the shoulder girdle stability time was 59 % in the first session and 100 % in the last session; in the frontal plane it was 28 % and 100 %, respectively, while in the scapular plane – 49 % (Appendix 8) and 99 % (Appendix 9).

During the performance of specific muscle tasks, the shoulder girdle stability time increased from 15 % in the first session to 92 % in the last session (Appendix 10).

3.1.3 Reliability of DAid smart shirt prototype measurements

The reliability of DAid smart shirt prototype measurements was evaluated by comparing three repeated shoulder girdle elevation measurements. The reliability of the left and right sensor measurements was evaluated using the Interclass Correlation Coefficient (ICC) and Cronbach's alpha coefficient.

ICC values for left-hand measurements: 0.91 (95 % CI 0.9–0.92) to 0.99 (95 % CI 0.99–0.99) ($p < 0.0001$). Cronbach's alpha coefficient values: 0.91 to 0.99.

ICC values for right-hand measurements: 0.91 (95 % CI 0.9–0.91) to 0.99 (95 % CI 0.99–0.99) ($p < 0.0001$). Cronbach's alpha coefficient values: 0.91 to 0.99.

3.1.4 Validity of DAid smart shirt prototype measurements

Validity was made for DAid smart shirt prototype measurements of the left and right sides. According to the Bland–Altman analysis both left and right-side measurements were valid compared with the “gold standard” method of 2D optical camera.

Eight seconds were used to measure the elevation, which includes shoulder rest measurements also. Seconds were divided into 0.5 s increments to see how many of the 21 measurements previously calculated did not fall within the 95 % confidence interval at that time point. A representation of the left and right shoulder band elevation displacement measurements is given in Appendix 11.

The measurements of the elevation displacement of the left and right shoulder girdle of a smart textile shirt are based on Blend-Altman analysis plots (see Graphic in Appendix 12).

3.2 Second stage

3.2.1 General characteristics of patients

The demographic characteristics of the group of study participants (n = 34) (age, gender, BMI), and the distribution of complaints of the dominant or leading hand in the study group are given in the Table 3.1.

Table 3.1

Characteristics of participants

Parameter	DAid smart shirt group	Control group	*p* values
Age (years)	38,6 (SD 12,6)	40,8 (SD 10,1)	0,053
Gender: women % (n)	58,8 (10)	52,9 (9)	0,730
BMI (kg/m^2)	22,0 (SD 1,5)	23,1 (SD 1,0)	0,027
Affected dominant hand % (n)	76,5 (13)	76,5 (13)	> 0,999

3.2.2 Additional qualitative variables

Adjunctive therapy methods

In patients with subacromial pain syndrome, training therapy is used as the main method of conservative therapy, which includes tasks of movement control, muscular strength, and AROM tasks. Complementary therapies – drug therapy and physical medicine – are not applied to everyone, but are tailored to the patient (Garving et al., 2017), so they were considered in the study to be confounding factors affecting the group homogeneity.

There was no statistically significant difference between the two groups after drug treatment (Kenalog 1.0 ml, Lidocaine 2 % 5.0 ml: 2 injections in the subacromial bursa; oral NSAIDs) and physical therapy procedures ($p = 0.697$).

Workload intensity in the context of the profession

The profession or activity and participation component of the study participants was identified as a confounding factor influencing the homogeneity of the groups.

Professions were divided into two groups:

a. low-intensity occupations: office workers, lecturers, students;
b. high-intensity occupations: ballet artists, physiotherapists, cooks, police officers, dog hairdressers, and fitness trainers.

According to the high and low-intensity workload of the represented profession, the two groups differed statistically significantly ($p = 0.071$), where the share of the low-intensity workload in the DAid shirt group was 47.1 %, but in the control group it was 82.4 %. The proportion of high-intensity occupations was 52.9 % in the DAid shirt group and 17.6 % in the control group.

High-intensity occupations were instructed not to restart their workload for as long as participation in the study did not affect the outcome of the study. Compliance was monitored with the question: “Is the instruction not to increase exercise intensity while participating in the study being followed?" The question was answered "Yes" in 100 % of cases.

Risk of shoulder injuries in the context of sports and leisure activities

The sports and leisure activities of the study participants or the activity and participation component were identified as confounding factors influencing the homogeneity of the groups.

Sports activities were divided into two groups:

a. low risk of injury to the shoulder joint and shoulder girdle (Ellenbecker, Wilk, 2016): motorsport, ballet, gardening, Nordic walking, athletics (running);

b. high risk of injury to the shoulder joint and shoulder girdle (Ellenbecker, Wilk, 2016): basketball, swimming, tennis, and volleyball.

The two groups did not differ statistically significantly according to the represented sport ($p = 0.730$).

Representatives in the high-risk group were instructed not to resume exercise for as long as they participated in the study so as not to affect the outcome of the study. Compliance was monitored with the question: "Is the instruction not to resume exercise intensity while participating in the study being followed?" The question was answered "Yes" in 100 % of cases.

3.2.3 DASH and functional test results

The DAid smart shirt group (n = 17) and the control group (n = 17) before and after the intervention for the treatment of subacromial pain syndrome were evaluated for functional status using self-reported DASH measurement and functional tests were performed after the intervention: shoulder joints ER and IR muscle isometric strength tests to determine the ER/IR ratio at the "90/0", "90/90" positions for the dominant (D) and non-dominant (ND) arm, and the

CKCUEST measurement. All the obtained data of each research participant can be viewed in the appendix: "Obtained values of research instruments by groups" (Appendix 13).

Results of DASH measurement before intervention

In the DAid shirt group, the DASH score before the intervention in the basic module was 54.4 (SD 2.5) (95 % CI 53.2–55.7) points, compared to 52.0 (SD 4.3) in the control group (95 % CI 49.8–54.2) points.

In the DAid shirt group, DASH values in the work module before intervention were 85.2 (CI 2.7) (95 % CI 83.8–86.6) points and 86.2 (SD 3.7) (95 % CI 84.3–88.1) points in the control group.

In the Sports module in the DAid shirt group, the DASH values were 83.8 (SD 2.7) (95 % CI 82.4–85.2) points and 84.4 (SD 3.2) (95 % CI 82.7–86.0) points.

The DASH score before the intervention did not differ statistically significantly between the DAid shirt group and the control group ($p > 0.05$).

Results of DASH measurement after intervention

The results in the Table 3.2 below show that statistically significant differences were observed between the groups before and after the measurements ($p < 0.001$). Obtained statistical power < 0.8 (0.99).

Table 3.2

DASH values before and after the intervention

	Before (± SD) (95 % CI)	**After (± SD) (95 % CI)**	**Mean difference (± SD) (95 % CI)**	***p* value and Cohen's *d* value**
DAid group	54.4 (± 2.5) (53.2–55.7)	14.7 (± 3.1) (13.1–16.2)	39.8 (± 4.1) (37.7–41.9)	< **0.001** (4.1)
Control group	52.0 (± 4.4) (49.8–54.2)	23.8 (± 3.2)	28.2 (± 5.3) (25.5–31.0)	< **0.001** (3.4)
p value and Cohen's *d* value	0.210	< **0.001** (2.4)		

Answering 4 questions in the DASH additional work module the results were obtained. The results in Table 3.3 below shows that statistically significant differences were observed between the groups before and after the measurements ($p < 0.001$). Obtained statistical power < 0.8 (1.00).

Table 3.3

DASH work module values before and after the intervention

	Before (± SD) (95 % CI)	**After (± SD) (95 % CI)**	**Mean difference (± SD) (95 % CI)**	***p* value and *r* value**
DAid group	85.2 (± 2.7) (83.8–86.6)	17.1 (± 3.3) (15.3–18.8)	68.2 (± 3.8) (66.2–70.1)	< **0.001** (0.9)
Control group	86.2 (± 3.7) (84.3–88.1)	27.5 (± 3.1) (25.9–29.1)	58.2 (± 5.3) (55.4–60.9)	< **0.001** (0.9)
p value and *r* value	0.424	< **0.001** (0.9)		

Answering 4 questions in the sports module the results were obtained. The results in Table 3.4 below show that statistically significant differences were observed between the groups before and after the measurements ($p < 0.001$). Obtained statistical power < 0.8 (0.98).

Table 3.4

DASH sport module values before and after the intervention

	Before (± SD) (95 % CI)	**After (± SD) (95 % CI)**	**Mean difference (± SN) (95 % TI)**	***p* value un Cohen's *d* value**
DAid group	83.8 (± 2.7) (82.4–85.2)	18.1 (± 3.3) (16.4–19.8)	66.3 (± 4.7) (63.9–68.8)	< **0.001** (4.7)
Control group	84.4 (± 3.2) (82.7–86.0)	25.7 (± 2.9) (24.2–27.2)	57.5 (± 3.1) (55.9–59.0)	< **0.001** (3.1)
p value and Cohen's *d* value	0.651	< **0.001** (2.4)		

CKCUEST results

After evaluating the study participants (n = 34) with the CKUES test, statistically significant differences between the results of the DAid shirt group and the control group were obtained (Appendix 14).

After the intervention, CKCUEST functional test score was 22.6 (SD 3.9) (95 % CI 20.2–24.2) in the DAid smart shirt group and 18.1 (SD 3.0) in the control group (95 % CI 16.6–19.7).

Comparing the test results, a statistically significant difference was found between the DAid shirt group and the control group ($p < 0.001$). Obtained statistical power < 0.8 (0.92).

ER/IR ratios at the "90/0" position

The ratio of external and internal rotational muscle forces at the "90/0" position (with the shoulder joint in 90° abduction and 0° in external rotation) was evaluated and calculated according to a standardized formula (ER : IR). The measurement results were obtained for both the dominant hand and the non-dominant hand (Appendix 15).

1) Measured values in the “90/0” position for the dominant hand

The ratio of external and internal rotational isometric muscle force for the dominant arm at position “90/0” in the DAid smart shirt group was 0.88 (SD 0.07) (95 % CI 0.85–0.92) and in the control group 0.65 (SD 0.09) (95 % CI 0.60–0.70).

The results of the dominant hand measurements of the ratio of the isometric muscle force of the external and internal rotation of the DAid smart shirt group and the control group differed statistically significantly ($p < 0.001$), and the obtained statistical power was < 0.8 (1.00).

2) Measured values in the “90/0” position for the non-dominant hand

The ratio of external and internal rotational isometric force for the non-dominant hand at position “90/0” in the DAid smart shirt group was 0.89 (SD 0.06) (95 % CI 0.86–0.93), while in the control group it was 0.62 (SD 0.1) (95 % CI 0.57–0.67).

The results of the non-dominant hand measurements of the external and internal rotational isometric muscle force ratios of the DAid smart shirt group and the control group differed statistically significantly ($p < 0.001$). Obtained statistical power < 0.8 (1.00).

ER/IR ratios at “90/90” position

The ratio of the force of the external and internal rotation in the “90/90” position (with the shoulder joint in 90° abduction and 90° in the external rotation) was evaluated and calculated according to the formula where the result obtained by the external rotation is divided by the result of the internal rotation. Measurement results were obtained for both the dominant hand and the non-dominant hand (Appendix 16).

1) Measured values in the “90/90” position for the dominant hand

The ratio of external and internal rotational isometric force for the dominant arm at position “90/90” in the DAid smart shirt group was 0.74 (SD 0.1) (95 % CI 0.67–0.81), while in the control group 0.56 (SD 0.09) (95 % CI 0.51–0.61).

The results of the dominant hand measurements of the ratio of the isometric force of the external and internal rotation of the DAid smart shirt group and the control group differed statistically significantly ($p < 0.001$). Obtained statistical power < 0.8 (0.99).

2) Measured values in the “90/90” position for the non-dominant hand

The ratio of external and internal rotational isometric force for the non-dominant arm at position “90/90” in the DAid smart shirt group was 0.77 (SD 0.1) (95 % CI 0.72–0.83), while in the control group it was 0.57 (SD 0.08) (95 % CI 0.53–0.61).

The results of the non-dominant hand measurements of the external and internal rotational isometric force ratios of the DAid smart shirt group and the control group differed statistically significantly ($p < 0.001$). Obtained statistical power < 0.8 (1.00).

4 Discussion

Use of smart shirt for patients with shoulder pathologies

Studies to date have focused on the development of a smart shirt using in volunteer populations or single-case studies (Tognetti et al., 2014; van Meulen et al., 2016; Lorussi et al., 2016) and not using them in the treatment of patients with shoulder pathologies such as subacromial pain syndrome.

The results of a case study conducted in a clinical setting show that DAid smart shirt prototype is an effective and objective tool for both patients and physiotherapists to use in the physiotherapy of subacromial pain syndrome. In addition to the generally accepted practice of physiotherapy, DAid smart shirt prototype can more objectively determine the ability to control movement by providing real-time feedback to both the patient and the physiotherapist (Semjonova et al., 2018).

Lorusi et al. has described the INTERACTION sensory platform, which is designed to monitor two patients in the home environment after a stroke as they perform daily activities (Lorussi et al., 2016). The information provided by the smart shirt system reflected the quality of physiological / pathological movement and movement performance at home after the clinical rehabilitation phase in the hospital (*ibid.*). Textile sensors were placed in the shoulder area to detect the compensatory movements of the shoulder blade (blade elevation and rotation) during a stretching activity during which shoulder joint abduction and rotation occur (*ibid.*). To this extent, the quality of movement performance in the upper extremity was evaluated (Park et al., 2003; Wang et al., 2015; van Meulen et al., 2016; Lorussi et al., 2016), but the results of post-intervention clinical trials were not evaluated, hence, this evaluation was carried out within the framework of this study providing insight into the useful application of the technology for motion control monitoring.

Also, in a study by Eizentals et al., it was concluded that knitted sensors are suitable for monitoring motion control tasks because they have a high sensitivity and can respond even to small compensatory movements that occur during motion control tasks. The knitted sensors ensure objective feedback during movement control tasks with a potential benefit for both the patient and the physiotherapist, and further research should be conducted in a wider patient population, a conclusion of this study (Eizentals et al., 2020). This was actually done in a randomized controlled trial in patients with subacromial pain syndrome using the DAid shirt technology prototype for movement control and musculoskeletal-specific tasks as outlined in the guidelines (Dierks et al., 2014; Elenbecker et al., 2016).

The results of the study show that patients with subacromial pain syndrome have better functional tests (ER/IR ratio, CKCUEST) and self-reported DASH measurement with DAid smart shirt prototype in the treatment process compared to conventional methods in a relatively small patient population. The population is more than one clinical case, leading to a positive trend in the development of a technology prototype with the potential to be used in the routine of physiotherapy in patients with shoulder pain.

Reliability and validity of DAid smart shirt prototype measurements

When looking at the results of clinical trials, the need for technology should be discussed and the reliability and validity of measurements should be assessed for a new technology to be used in a clinical setting (Germanotta et al., 2020; Roggio et al., 2021). What has been done in this work and the results obtained show the excellent reliability and validity of DAid smart shirt prototype measurements compared to the "gold standard" of motion measurement.

The reliability and validity of the measurements for these sensors are adequate to objectively assess the movement of both the lower extremities (Januskevica et al., 2020), which is one of the preconditions for the application of new technology in physiotherapy.

Results of self-reported DASH measurement in patients with SAPS

To evaluate the usefulness of the application of new technology, its impact on the results of physiotherapy should be assessed, whether it is a functional test or the patient's assessment of the course of treatment by filling in self-reported standardized questionnaires.

The DAid smart shirt group (n = 17) and the control group (n = 17) before and after the intervention for subacromial pain syndrome were evaluated for functional status using self-reported DASH measurement to assess pain and disability levels during daily activities.

The results of the study show that after 8 weeks of intervention, the results of self-reported DASH measurement in all modules (basic, work, and sports) have improved in both the DAid smart shirt prototype group and the control group. And the results after 8 weeks of intervention are similar to the overall measurement results in the population (Hunsaker et al., 2002).

The results of the DASH evaluation obtained in this study are similar to those described by Moslehi et al. study – this group of researchers also evaluated the results of the study participants after 8 weeks of intervention by measuring DASH, and the score obtained was 13.2 points (SD 7.4) for the group using the feedback method, 17.3 points (SD 6.5) for the group that received exercise therapy without video feedback, and 25.0 points (SD 7.2) for the control group (Moslehi et al., 2020).

DASH is a self-reported assessment of the outcome and course of physiotherapy; The DAid smart shirt is a tool that promotes the patient's independence in the treatment process, there is reason to believe that it is interrelated that the patient has significant independence in the treatment process, which affects the same assessment of the treatment process. And the clinically significant difference and improvement are directly or indirectly due to the use of feedback generated by the prototype DAid smart shirt technology.

CKCUEST results in patients with SAPS

The CKCUEST functional test evaluates the stability of the upper limb in the closed kinematic chain position, which is one of the few objective tests that has been developed to date and is easy to use in the evaluation of the functional condition of the shoulder girdle in a physiotherapy environment (Cools et al., 2020). The use of a functional test in acute and subacute pain in patients with subacromial pain syndrome is contraindicated (Tucci et al., 2017), so the functional test was performed only after the intervention.

When evaluating study participants (n = 34) after intervention with CKCUEST, statistically significant differences were obtained between the DAid shirt group and the control group, indicating that using the DAid shirt technology prototype in the initial phase of physiotherapy and in combination with muscle-specific tasks in the second phase, patients achieve better results in the functional tasks for the shoulder. The results obtained differed from the test results obtained in the general population of healthy, physically active people (Tucci et al., 2014; Tucci et al., 2017), they were lower. However, it should be noted that participants in both groups were evaluated after an 8-week intervention in the first two phases of physiotherapy before starting sport-specific physiotherapy tasks, and patients are not yet fully referred to as "healthy, physically active people" without SAPS. However, since after this stage the DAid smart shirt prototype group performed better than the control group, the test results obtained in a healthy, physically active population can be achieved faster than if the first stages were performed without DAid smart shirt prototype feedback.

Results of the ER/IR ratio in patients with SAPS

An appropriate ratio of the forces of the external and internal rotators of the shoulder joint is an important indicator for the patient to return to activity after injury to the shoulder joint or subacromial pain syndrome (Cools et al., 2016). The study evaluated the power ratio of the external and internal rotators at the “90/0” position and the “90/90” position.

The obtained results show that the application of DAid smart textile shirt technology in the treatment process in patients with subacromial pain syndrome provides similar ER/IR ratios as in the general population of healthy volunteers (Cools et al., 2016).

The ER/IR ratio of the control group was statistically significantly lower than that of the DAid smart shirt group. This indicates that by combining muscle-specific strength training with shoulder position control tasks, better results are obtained in increasing the local muscle strength of the shoulder joint. This is also in line with Ann Cool's recommendations for shoulder physiotherapy, where control of the shoulder girdle position is important not only in the initial phase of shoulder pain physiotherapy but until the patient returns to normal activity and also prophylactically (Cools et al., 2020).

Feedback used in physiotherapy for patients with shoulder pathologies

In a randomized controlled trial, study participants were divided into two groups: the DAid smart shirt group and the control group. The members of the DAid smart shirt group had to perform tasks dressed in DAid smart shirt technology. The participant monitored the quality of the task by looking at the computer screen.

Statistically significant improvements were observed in both the study group and the control group, however, in the study group using the DAid smart shirt feedback principle during the tasks, the test results were statistically significantly better than in the control group without the DAid smart shirt applied.

A study by Moslehi et al. published in 2020 found that the use of feedback in patients with subacromial pain syndrome helps to effectively improve functionality and reduce pain (Moslehi et al., 2020). The study used video feedback: the participants were filmed from behind while training in the position of the shoulder girdle, rotator cuff muscle strength training, as well as tasks to promote shoulder joint movement. The duration of the intervention was also 8 weeks, as in the study described in the Doctoral Thesis.

Conclusion of the study of Moslehi et al. – using the feedback method in patients with subacromial pain syndrome, the parameters of pain, disability and functionality improve significantly, which coincides with the results of the study described in this Doctoral Thesis.

A significant difference between Moslehi et al. research and Doctoral Thesis research is the feedback tool used by Moslehi et al. There was video feedback in the case, but in the Doctoral Thesis, a prototype of a DAid smart shirt was used. Video equipment is inconvenient to use in a physiotherapy routine, it is expensive and time-consuming to install. Also, the video does not provide selective feedback to the patient. DAid's smart shirt technology, on the other hand, is sensitive to even the slightest change in the position of the shoulder girdle, it is convenient for the patient because the sensors are on sportswear and the feedback information is selective – there is only one selective curve on the computer screen. This makes it easier for the patient to focus on one curve throughout the task.

Benefits of using smart technologies for physiotherapy patients

According to the results of the study, the use of intelligent technologies has a beneficial clinical effect on patient function and reduction of symptoms. Compared to well-established therapies that provide feedback from the physiotherapist or monitor the patient's performance in the mirror, the use of smart technology feedback contributes to more independent physiotherapy for the patient and independent of the clinical staff.

An example is a Valdeo system (Hocoma AG, Courtesy of Hocoma, Switzerland), which can be used in home rehabilitation for patients with chronic low back pain. Sensors that are attached to the body provide feedback on the quality of task performance, allowing for improved performance, motivating the patient, and promoting patient independence (Patel et al., 2012).

Another example of a system that can be used outside the clinical setting is the Philips stroke rehabilitation exerciser, which is used to help restore motor function after a stroke. During the task, a wireless sensor system is added to the patient, which allows for analyzing the quality of the performed tasks in real-time, provides feedback to the patient, and promotes his / her independence in daily activities (Willmann et al., 2007).

One of the reasons why the information provided by smart technologies is more desirable to the patient – the patient focuses on the task and the feedback. In the generally accepted method, when the feedback is provided by the physiotherapist, the patient's attention is focused not on the quality of the performance of his task, but the feedback provided by the physiotherapist, and this hinders the patient's independence.

During the performance of physiotherapy tasks, the reflection in the mirror often serves as a source of feedback. Looking in the mirror, a large amount of visual information is obtained, but the eye may not notice a slight change in the quality of the movement. The sensitivity of the sensor systems to movements and the ability to detect small movements are better, so the feedback is more accurate in real-time.

In addition, the feedback provided is often in the form of a curve, a dot, or a symbol – as shown by studies that analyse brain activity and information perception during tasks, it is easier for the brain to perceive selective information, making it easier to hold attention during the task. (Parks et al., 2013; Sturmberg et al., 2013).

Promoting patient independence in SAPS

The World Health Organization states that the goal of rehabilitation is to promote an individual's ability to function independently, promote independence from carers, and reduce barriers that affect an individual's activity and interaction with the real environment.

Smart technologies such as the DAid shirt promote patient / individual independence and independence in the individual's real everyday environment, as they include training in the quality of movement during the task, training to perform the task without using an abnormal movement pattern, and independent task monitoring following the feedback provided by the on-screen information. This is independence from the physiotherapist for most of the rehabilitation period for pathologies such as subacromial pain syndrome, and such independence has a significant clinical effect. This is also shown by the study by Santello et al. on rehabilitation at home without the supervision of a physiotherapist (Santello et al., 2020). During a randomized controlled trial, patients / study participants were trained for home tasks and provided with handouts in DVD format with task descriptions to be completed in 2 months or 8 weeks. The tasks included strength exercises and movement-enhancing exercises. After 8 weeks of intervention, participants with subacromial pain syndrome showed a reduction in pain, reduction in disability, and improvement in function (Santello et al., 2020).

Promoting independence and educating the patient is the most important component of rehabilitation in subacromial pain syndrome, because in the long run it is more efficient and reduces surgical interventions by 80 % (Holmgren et al., 2012).

Prospects for SAPS rehabilitation cost reduction

Promoting patient independence during activities and long-term education reduces the cost of rehabilitation. A Swedish study has collected data on the costs of shoulder pathology in primary care (Virta et al., 2012). The data were obtained from two Swedish municipalities / cities.

The average cost in Sweden for a 60-minute physiotherapist's consultation is € 50, a 25-minute GP consultation is € 107, orthopaedic surgery consultation is € 335, shoulder surgery costs an average of € 2,420, and a sick leave costs € 205 per day (Virta et al., 2012). It should be noted that in cases of shoulder pain, the patient visits a physiotherapist on average 3–4 times during the rehabilitation phase. If the patient is being treated on an outpatient basis under the supervision of a physiotherapist, this figure may reach 8.2 to 13.62 times in 8 weeks. The cost of a physiotherapy service then amounts to € 409–680 per patient, which is 60 % of the total rehabilitation cost (Virta et al., 2012).

The costs of physiotherapy services in Sweden are similar to those in Latvia when a patient visits private institutions providing rehabilitation – the so-called physiotherapy services for musculoskeletal disorders. Therefore, it is important to look for solutions to promote the patient's independence in daily activities and interaction with the real environment. Smart technology is a way to ensure that a patient with non-specific shoulder pain is independent in their daily activities, independent in their rehabilitation process, and able to make decisions related to their health. Thus, the financial burden on the patient or the expenses from the state budget would be reduced if health care services were provided in state or municipal medical institutions.

DAid shirt technology is designed for monitoring the shoulder girdle during tasks performed in routine by a physiotherapist. Thus, DAid's smart shirt technology might reduce the number of visits to physiotherapist for patients with subacromial pain syndrome, reducing health costs. The technology is easy and convenient to use without requiring a long training course.

Topicality of remote musculoskeletal rehabilitation

The discussion topics discussed above focused on the application of smart technologies, including DAid smart shirt, and the benefits of their application in physiotherapy.

This work has been completed between 2018, when it was planned and developed, and early 2021. The practical part of the study had to be stopped in early 2020 due to the pandemic caused by Covid-19.

In 2019, the World Health Organization published Guidelines on the Use of Digital Interventions to Strengthen the Health System, which defined the role and benefits of information and communication technologies in medicine when medical interventions were used. The guidelines also set out a plan for measures that would be desirable and needed to better integrate information and communication technologies into healthcare. Recommendations have been developed for medical users (patients / clients), medical service providers, healthcare system organizers, and data processing companies.

The integration of information and communication technologies into routine practice is a new challenge of this age, requiring adequate data security in the digital environment, reliability and validity of information, standardization of systems, and data processing and storage (Cheng & Mitomo, 2017; Casselman et al., 2017). However, technology is a solution to population aging, overcrowding, and the physical inaccessibility of medical services that more and more people are facing (Casselman et al., 2017). The DAid smart shirt is a way to provide rehabilitation services remotely, which is one of the goals of telemedicine. But, like any new system, the DAid smart shirt prototype needs development, improvement, and commercialization.

Limitations of the study

One of the main limiting factors for this study was the declaration of a national emergency due to the Covid-19 virus pandemic.

The practical part of the study was scheduled to run from January 2019 to May 2020, with 25 participants per group to achieve a difference of at least 15.1 points between groups in the DASH questionnaire – the number of participants included in the study affects patients with subacromial pain syndrome (Feedback improves the scapular-focused treatment effects in patients with shoulder impingement syndrome) by Moslehi et al. (Moslehi et al., 2020). However, instead of 50 participants, only 34 participated in the DAid shirt group and 17 in the control group.

It is important to highlight that research to date has focused on the development of smart clothing systems or their prototypes in small volunteer populations or case studies (Tognetti et al., 2014; van Meulen et al., 2016; Lorussi et al., 2016; Eizentals et al., 2020). To date, no analogous studies have been performed with larger patient populations using smart textile clothing or prototypes.

The DAid smart shirt prototype is not commercially available, it is not a "mature" technology, so the number of patients involved also depends on whether the technology can "technically survive" the study.

The design of the study should also be mentioned: for a randomized controlled trial to have a higher level of confidence, it should be double-blind, excluding the placebo effect. Due to the specifics of rehabilitation as a field, it was not possible to perform a double-blind study, because a physiotherapist needs to know what task is intended for a particular patient / participant, which is also indicated by Eizentals et al. In a study conducted in 2020 (Eizentals et al., 2020). Also, the DAid smart shirt patient group knew they were in the DAid smart shirt group. Therefore, one of the systemic errors (bias) was that the members of the DAid smart shirt group, especially those who had experienced shoulder pain several times, were more positive about the treatment process, as it was a "novelty" in physiotherapy.

A final limitation of the study is the fact that a person sweats in close-fitting clothing during physical activities, thus altering the ability of the smart textile sensor to conduct electrical impulses. This should be kept in mind by the physiotherapist when assessing the intensity of the exercise to be recommended to the patient. Movement control tasks do not require much effort, and tasks required for the rehabilitation of shoulder patients can be applied without promoting excessive patient sweating. On the other hand, when performing tasks / exercises in the smart shirt that require working with a submaximal weight for the shoulder girdle, the data on the screen will be erroneous / inappropriate.

Further development directions and research topics

The author of Doctoral Theses puts forward 9 possible further directions to move on based on obtained results. The other 10 can be viewed in the full version of the Doctoral Thesis.

1. Improve smart shirt technology so that its production is an automatic process that does not have to be done by hand.

2. Adapt Daid smart shirt prototype for people with visual and hearing impairments.
3. Application of a prototype of DAid smart shirt prototype in cases of other shoulder pathologies.
4. To continue the development of the DAid smart shirt prototype to be able to apply it to wider populations.
5. Use a prototype DAid shirt outside the laboratory and physiotherapeutic environment.
6. Feedback from the user of the technology prototype is also required.
7. What would be the most optimal type of feedback (e.g., audial, visual, tactile; all together or in combination) for patients with shoulder pain to achieve the most positive clinical outcome in the shortest possible time.
8. What are the outcomes of therapy when DAid smart shirt is used in a chronic pain patient population. Does technology also have a positive effect on their treatment process?
9. Does the use of smart technology motivate patients to take action to improve and / or prevent their health?

Conclusions

1. The DAid smart shirt prototype, which registers the position of the shoulder girdle, can be used as objective feedback during a physiotherapeutic intervention.
2. The DAid smart shirt prototype measurements are reliable and valid compared with the "gold standard" and are suitable as objective feedback in physiotherapy for patients with subacromial pain syndrome for shoulder girdle monitoring during functional shoulder girdle tasks.
3. Using the DAid smart shirt prototype in physiotherapy of patients with subacromial pain syndrome, better results of functional tests (ER/IR ratio, CKCUEST) are achieved in comparison with conventional methods.
4. Using the DAid smart shirt prototype in physiotherapy of patients with subacromial pain syndrome, better results of self-reported DASH measurement are achieved compared to conventional methods.

Publications and reports on the topic of the Doctoral Thesis

Scientific publications included in international databases (Web of Science, SCOPUS):

1. **Semjonova, G.,** Vetra, J., Okss, A., Katashev, A. Development of a New Method to Monitor Shoulder Girdle Motion for Ballerina with Shoulder Impingement Syndrome Based on DAid Smart Shirt Application. In: Lhotska, L., Sukupova, L., Lacković, I., Ibbott, G. (eds) *World Congress on Medical Physics and Biomedical Engineering 2018. IFMBE Proceedings*, vol 68/2. Springer, Singapore.
2. **Semjonova, G.,** Vetra, J., Okss, A., Katashev, A., Cauce, V. 2019. Reliability of the DAid Smart Shirt for Shoulder Girdle Motion Assessment in High String Players. *SOCIETY.INTEGRATION.EDUCATION. Proceedings of the International Scientific Conference. Volume IV. Sports and Health. Art and Design.* Rezekne, Rezekne Academy of Technologies, 574.
3. **Semjonova, G.,** Vetra, J., Okss, A., Katashev, A. and Cauce, V. 2019. Assessment of Shoulder Girdle Elevation Motion using Daid Smart Shirt: A Reliability and Validity Study. *In Proceedings of the 7th International Conference on Sport Sciences Research and Technology Support*, Volume 1: K-BioS, ISBN 978-989-758-383-4, 229–235. DOI: 10.5220/0008064802290235
4. Eizentals, P., Katashev, A., Okss, A. & **Semjonova, G.** 2020. Smart Shirt for Uncontrolled Movement Retraining. *IFMBE Proceedings*, *76*. https://doi.org/10.1007/978-3-030-31635-8_113
5. Eizentals, P., Katashev, A., Okss, A., **Semjonova, G.** 2020. Smart shirt system for compensatory movement retraining assistance: feasibility study. *Health Technol*. 10, 861–874. https://doi.org/10.1007/s12553-020-00420-x
6. **Semjonova, G.**, Vetra, J., Cauce, V., Okss, A., Katashev, A. & Eizentals, P. 2020. Improving the recovery of patients with subacromial pain syndrome with the daid smart textile shirt. *Sensors (Switzerland)*, 20(18), 1–14. https://doi.org/10.3390/s20185277

Scientific publications in the international databases (Web of Science, SCOPUS) on the use of smart textile in rehabilitation:

1. Baribina, N., Okss, A., Baltina, I., Katashev, A., **Semjonova, G**. & Bergmane, E. 2019. Development of Pressure Sensitive Glove Prototype. *In Key Engineering Materials,* Vol. 800, 326–330. Trans Tech Publications.
2. Januskevica, A., **Semjonova, G**., Okss, A., Katashev, A. & Eizentals, P. 2020. *Evaluation of the Foot Performance in "Single Leg Squat" Test of Female Athletes using Smart Socks*. *icSPORTS*, 161–168. https://doi.org/10.5220/0010146701610168

Presentation at an international scientific conference with an oral report or thesis not included in international databases:

1. Semjonova, G., Vetra, J., Okss, A., Katashev, A. 2017. Smart Shirt With Textile Strain Sensors as Experimental Method for Ballerina Shoulder Girdle Motion Control. *5th International Conference on Physiotherapy*, 27.–29. XI, Dubai, UAE. (report).

2. Semjonova, G., Vetra, J., Okss, A., Katashev, A. 2018. DAid Smart Shirt as Experimental Application for Ballerina Shoulder Girdle Motion Control (Proof of Concept). *10th International Baltic Sports Medicine Congress*, 20.–21. V, Riga, Latvia. (oral report).

3. Semjonova, G., Vetra, J., Okss, A., Katashev, A. 2018. Development of a New Method to Monitor Shoulder Girdle Motion for Ballerina With Shoulder Impingement Syndrome Based on DAid Smart – Shirt Application. *IUPESM World Congress on Medical Physics and Biomedical Engineering*, 3.–8. VI, Prague, Czech Republic. (oral report).

4. **Semjonova, G.**, Vetra, J., Okss, A., Katashev, A., Cauce, V. 2018. Reliability of the DAid Smart Shirt for Shoulder Girdle Motion Assessment During Violin Performance. *2nd International Congress on Musicians Physiotherapy,* 6.–8. IX, Osnabruck, Germany. (oral report).

5. **Semjonova, G.**, Vetra, J., Okss, A., Katashev, A., Cauce, V. 2019. Reliability and Validity of the DAid Smart – Shirt for Shoulder Girdle Elevation Motion Assessment. *World Confederation for Physiotherapy Congress,* 10.–14. V, Geneva, Switzerland. (report).

6. **Semjonova, G.**, Vetra, J., Okss, A., Katashev, A., Cauce, V. 2019. Reliability of the DAid Smart Shirt for Shoulder Girdle Motion Assessment in High String Players. *International Scientific Conference "Society, Integration, Education"*, 24.–25. V, Rezekne, Latvia. (oral report).

Bibliography

Books:

1. Allen, K., Anderson, M., Balady, G. 2014. *ACSM's Guidelines for Excercise Testing and Prescription. Ninth edition.* United States of America: Wolters Kluwer Health. Lippincott Williams &Wilkins.

2. Cools, A., Borms, D., Castelein, B. et al. 2020. *Shoulder Rehabilitation. A Practical Guide for the Clinician.* Belgium: SKRIBIS.

3. Comford, M., Mottram, S. 2012. *Kinetic Control. The Management of Uncontroled Movement.* Australia: Churchill Livingstone, ELSEVIER.

4. Ellenbecker, T. S., Wilk, K. E. 2016. *Sport therapy for the shoulder: evaluation, rehabilitation, and return to sport.* United States of America: Human Kinetics.

5. Ellenbecker, T. S., Bailie, D. S. 2010. The Shoulder. In: Donatelli, R., Wooden, M. ed. *Orthopaedic Physical Therapy, Fourth edition.* United States of America: Churchil Livingstone. ELSEVIER. 197–237.

6. Pelgrom, Marcel J. M. 2013. Analog-to-digital conversion. *Analog-to-Digital Conversion*. Springer, New York, NY, 325–418.

Periodicals:

7. Bet-Or, Y., van den Hoorn, W., Johnston, V., and O'Leary, S. 2017. Reliability and validity of an acromion marker cluster for recording scapula posture at end range clavicle protraction, retraction, elevation, and depression. *Journal of applied biomechanics*, 33(5), 379–383.

8. Casselman, J., Onopa, N., and Khansa, L. 2017. Wearable healthcare: Lessons from the past and a peek into the future. *Telematics and Informatics*, 34(7), 1011–1023. https://doi.org/10.1016/j.tele.2017.04.011

9. Cheng, J. W., and Mitomo, H. 2017. The underlying factors of the perceived usefulness of using smart wearable devices for disaster applications. *Telematics and Informatics*, 34(2), 528–539.

10. Cools, A. M. J., Vanderstukken, F., Vereecken, F., Duprez, M., Heyman, K., Goethals, N., and Johansson, F. 2016. Eccentric and isometric shoulder rotator cuff strength testing using a hand-held dynamometer: reference values for overhead athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 24(12), 3838–3847. https://doi.org/10.1007/s00167-015-3755-9

11. Cools, A. M. J., Struyf, F., de Mey, K., Maenhout, A., Castelein, B., and Cagnie, B. 2014. Rehabilitation of scapular dyskinesis: From the office worker to the elite overhead athlete. *British Journal of Sports Medicine*, 48(8), 692–697. https://doi.org/10.1136/bjsports-2013-092148

12. Diercks, R., Bron, C., Dorrestijn, O., Meskers, C., Naber, R., de Ruiter, T., Willems, J., Winters, J., and van der Woude, H. J. 2014. Guideline for diagnosis and treatment of subacromial pain syndrome. *Acta Orthopaedica*, 85(3), 314–322. https://doi.org/10.3109/17453674.2014.920991

13. Dijkstra, H. P., Ergen, E., Holtzhausen, L., Beasley, I., Alonso, J. M., Geertsema, L., Geertsema, C., Nelis, S., Ngai, A. S. H., Stankovic, I., Targett, S., and Andersen, T. E. 2020. Remote assessment in sport and exercise medicine (SEM): A narrative review and teleSEM solutions for and beyond the COVID-19 pandemic. *British Journal of Sports Medicine*, 54(19), 1162–1167. https://doi.org/10.1136/bjsports-2020-102650

14. Eizentals, P., Katashev, A., Oks, A., and Semjonova, G. 2020. Smart Shirt for Uncontrolled Movement Retraining. *IFMBE Proceedings*, 76. https://doi.org/10.1007/978-3-030-31635-8_113

15. Ellenbecker, T. S., and Cools, A. 2010. Rehabilitation of shoulder impingement syndrome and rotator cuff injuries: An evidence-based review. *British Journal of Sports Medicine*, 44(5), 319–327. https://doi.org/10.1136/bjsm.2009.058875

16. Franchignoni, F., Vercelli, S., Giordano, A., Sartorio, F., Bravini, E., and Ferriero, G. 2014. Minimal clinically important difference of the disabilities of the arm, shoulder and hand outcome measure (DASH) and its shortened version (quickDASH). *Journal of Orthopaedic and Sports Physical Therapy*, 44(1), 30–39. https://doi.org/10.2519/jospt.2014.4893

17. Garving, C., Jakob, S., Bauer, I., Nadjar, R., and Brunner, U. H. 2017. Impingement syndrome of the shoulder. *Deutsches Arzteblatt International*, 114(45), 765–776. https://doi.org/10.3238/arztebl.2017.0765

18. Germanotta, M., Gower, V., Papadopoulou, D. et al. Reliability, validity and discriminant ability of a robotic device for finger training in patients with subacute stroke. *Journal of NeuroEngineering and Rehabilitation*, 17, 1 2020. https://doi.org/10.1186/s12984-019-0634-5

19. Giavarina. J. 2015. Understanding Bland Altman analysis. *Biochemia Medica*, 25(2):141–51. http://dx.doi.org/10.11613/BM.2015.015

20. Holmgren, T., Hallgren, H. B., Öberg, B., Adolfsson, L., and Johansson, K. 2012. Effect of specific exercise strategy on need for surgery in patients with subacromial impingement syndrome: Randomised controlled study. *BMJ (Online)*, 344(7846), 1–9. https://doi.org/10.1136/bmj.e787

21. Hunsaker, F. G., Cioffi, D. A., Amadio, P. C., Wright, J. G., and Caughlin, B. 2002. The American Academy of Orthopaedic Surgeons outcomes instruments: Normative values from the general population. *Journal of Bone and Joint Surgery – Series A*, 84(2), 208–215. https://doi.org/10.2106/00004623-200202000-00007

22. Januskevica, A., Semjonova, G., Oks, A., Katashev, A. & Eizentals, P. 2020. Evaluation of the Foot Performance in "Single Leg Squat" Test of Female Athletes using Smart Socks. *In icSPORTS*, 161–168.

23. Juel, N. G., and Natvig, B. 2014. Shoulder diagnoses in secondary care, a one year cohort. *BMC Musculoskeletal Disorders*, 15(1), 1–8. https://doi.org/10.1186/1471-2474-15-89

24. Klintberg, I. H., Cools, A. M. J., Holmgren, T. M., Holzhausen, A. C. G., Johansson, K., Maenhout, A. G., Moser, J. S., Spunton, V., and Ginn, K. 2015. Consensus for physiotherapy for shoulder pain. *International Orthopaedics*, 39(4), 715–720. https://doi.org/10.1007/s00264-014-2639-9

25. Lauber, B. & Keller, M. 2014. Improving motor performance: selected aspects of augmented feedback in exercise and health. *European journal of sport science*, 14(1), 36–43.

26. Lorussi, F., Carbonaro, N., de Rossi, D., Paradiso, R., Veltink, P., and Tognetti, A. 2016. Wearable Textile Platform for Assessing Stroke Patient Treatment in Daily Life Conditions. *Frontiers in Bioengineering and Biotechnology*, 4(MAR). https://doi.org/10.3389/fbioe.2016.00028

27. Luime, J. J., Koes, B. W., Hendriksen, I. J. M., Burdorf, A., Verhagen, A. P., Miedema, H. S., and Verhaar, J. A. N. 2004. Prevalence and incidence of shoulder pain in the general population; a systematic review. *Scandinavian Journal of Rheumatology*, 33(2), 73–81. https://doi.org/10.1080/03009740310004667

28. McGraw, K. O., Wong, S. P. 1996. Forming Inferences About Some Intraclass Correlation Coefficients. *Psychological Methods*, Vol. l, No 1, 30–46.

29. Moslehi, M., Letafatkar, A., and Miri, H. 2020. Feedback improves the scapular-focused treatment effects in patients with shoulder impingement syndrome. *Knee Surgery, Sports Traumatology, Arthroscopy*, 0123456789. https://doi.org/10.1007/s00167-020-06178-z

30. Mokhlespour Esfahani M. I., Zobeiri, O., Moshiri, B. et al. 2017. *Trunk Motion System (TMS) Using Printed Body Worn Sensor (BWS) via Data Fusion Approach*. Leonhardt, S., Teichmann, D., eds. Sensors (Basel, Switzerland). 17(1):112. doi:10.3390/s17010112.

31. O'Keeffe, M., Cullinane, P., Hurley, J., Leahy, I., Bunzli, S., O'Sullivan, P. B. & O'Sullivan, K. 2016. What influences patient-therapist interactions in musculoskeletal physical therapy? Qualitative systematic review and meta-synthesis. *Physical therapy*, 96(5), 609–622.

32. Oks, A., Katashev, A., and Litvak, J. 2015. Knitted Resistive Fabric: Properties and Applications. Materials Science. *Textile and Clothing Technology*, 9(21), 28. https://doi.org/10.7250/mstct.2014.005

33. Oks, A., Katashev, A., Zadinans M., Rancans, M., Litvak, J. 2016. Development of Smart Sock System for Gate Analysis and Foot Pressure Control. *Conference paper*.

34. Park, S., and Jayaraman, S. 2003. Enhancing the quality of life through wearable technology. *IEEE Engineering in medicine and biology magazine*, 22(3), 41–48.

35. Parks, E. L., and Madden, D. J. 2013. Brain connectivity and visual attention. *Brain connectivity*, 3(4), 317–338.

36. Patel, S., Park, H., Bonato, P., Chan, L., and Rodgers, M. 2012. A review of wearable sensors and systems with application in rehabilitation. *Journal of neuroengineering and rehabilitation*, 9(1), 1–17.

37. Pieters, L., Lewis, J., Kuppens, K., Jochems, J., Bruijstens, T., Joossens, L., and Struyf, F. 2020. An update of systematic reviews examining the effectiveness of conservative physical therapy interventions for subacromial shoulder pain. *Journal of Orthopaedic and Sports Physical Therapy*, 50(3), 131–141. https://doi.org/10.2519/jospt.2020.8498

38. Reilingh, M. L., Kuijpers, T., Tanja-Harfterkamp, A. M., and van der Windt, D. A. 2008. Course and prognosis of shoulder symptoms in general practice. *Rheumatology*, 47(5), 724–730. https://doi.org/10.1093/rheumatology/ken044

39. Reinold, M. M., Escamilla, R., and Wilk, K. E. 2009. Current concepts in the scientific and clinical rationale behind exercises for glenohumeral and scapulothoracic musculature. *Journal of Orthopaedic and Sports Physical Therapy*, 39(2), 105–117. https://doi.org/10.2519/jospt.2009.2835

40. Roggio, F., Ravalli, S., Maugeri, G., Bianco, A., Palma, A., Di Rosa, M. & Musumeci, G. 2021. Technological advancements in the analysis of human motion and posture management through digital devices. *World Journal of Orthopedics*, 12(7), 467.

41. Santello, G., Rossi, D. M., Martins, J., Libardoni, T. D. C., and de Oliveira, A. S. 2020. Effects on shoulder pain and disability of teaching patients with shoulder pain a home-based exercise program: A randomized controlled trial. *Clinical Rehabilitation*, 34(10), 1245–1255.

42. Sullivan, M., Moldafsky, D., Durbin, C. R., Bond, E., Foster, N., Greenberg, A. M., Krump, J., McSween, J., Seales, S. & Sun, R. 2015. *Defense Advanced Research Projects Agency: Key Factors Drive Transition of Technologies, but Better Training and Data Dissemination Can Increase Success.*

43. Steuri, R., Sattelmayer, M., Elsig, S., Kolly, C., Tal, A., Taeymans, J., and Hilfiker, R. 2017. Effectiveness of conservative interventions including exercise, manual therapy and medical management in adults with shoulder impingement: A systematic review and meta-analysis of RCTs. *British Journal of Sports Medicine*, 51(18), 1340–1347. https://doi.org/10.1136/bjsports-2016-096515

44. Sturmberg, C., Marquez, J., Heneghan, N., Snodgrass, S., and van Vliet, P. 2013. Attentional focus of feedback and instructions in the treatment of musculoskeletal dysfunction: a systematic review. *Manual therapy*, 18(6), 458–467.

45. Tognetti, A., Lorussi, F., Dalle Mura, G., Carbonaro, N., Pacelli, M., Paradiso, R., and de Rossi, D. 2014. New generation of wearable goniometers for motion capture systems. *Journal of neuroengineering and rehabilitation*, 11(1), 1–17.

46. Tucci, H. T., Martins, J., Sposito, G. D. C., Camarini, P. M. F., and de Oliveira, A. S. 2014. Closed Kinetic Chain Upper Extremity Stability test (CKCUES test): A reliability study in persons with and without shoulder impingement syndrome. *BMC Musculoskeletal Disorders*, 15(1), 1–9. https://doi.org/10.1186/1471-2474-15-1

47. Tucci, H. T., Felicio, L. R., McQuade, K. J., Bevilaqua-Grossi, D., Camarini, P. M. F. & Oliveira, A. S. 2017. Biomechanical analysis of the closed kinetic chain upper-extremity stability test. *Journal of sport rehabilitation*, 26(1), 42–50.

48. Van Meulen, F. B., Klaassen, B., Held, J., Reenalda, J., Buurke, J. H., van Beijnum, B. J. F., and Veltink, P. H. 2016. Objective evaluation of the quality of movement in daily life after stroke. *Frontiers in bioengineering and biotechnology*, 3, 210.

49. Virta, L., Joranger, P., Brox, J., and Eriksson, R. 2012. Costs of shoulder pain and resource use in primary health care: A cost-of-illness study in Sweden. *BMC Musculoskeletal Disorders*, 13(1), 17. https://doi.org/10.1186/1471-2474-13-17

50. Watts, A. R., Williams, B., Kim, S. W., Bramwell, D. C., and Krishnan, J. 2017. Shoulder impingement syndrome: a systematic review of clinical trial participant selection criteria. *Shoulder and Elbow*, 9(1), 31–41. https://doi.org/10.1177/1758573216663201

51. Wang, Q., Markopoulos, P., Yu, B., Chen, W., and Timmermans, A. 2017. Interactive wearable systems for upper body rehabilitation: A systematic review. *Journal of NeuroEngineering and Rehabilitation*, 14(1), 1–21. https://doi.org/10.1186/s12984-017-0229-y

52. Wang, Q., Chen, W., Timmermans, A. A. A., Karachristos, C., Martens, J. B., Markopoulos, P. 2015. Smart Rehabilitation Garment for posture monitoring. *In Proceedings of the 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Milan, Italy, 25–29 August 2015, 5736.

53. Willmann, R. D., Lanfermann, G., Saini, P., Timmermans, A., te Vrugt, J., and Winter, S. 2007. Home stroke rehabilitation for the upper limbs. *In 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 4015–4018. IEEE.

54. Worsley, P., Warner, M., Mottram, S., Gadola, S., Veeger, H. E. J., Hermens, H., and Stokes, M. 2013. Motor control retraining exercises for shoulder impingement: effects on function, muscle activation, and biomechanics in young adults. *Journal of shoulder and elbow surgery*, 22(4), e11–e19.

55. Wu, G., van der Helm, F. C., Veeger, H. D., Makhsous, M., van Roy, P., Anglin, C., and Buchholz, B. 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion –Part II: shoulder, elbow, wrist and hand. *Journal of biomechanics*, 38(5), 981–992.

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Appendices

Appendix 1

Second stage exercises (description in Latvian)

Kustības kontroles uzdevumi

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		[illegible]	
[illegible]		[illegible]	
[illegible]		[illegible]	
[illegible]		[illegible]	

1 [illegible]

2 [illegible]

Appendix 2

Muscle-specific tasks (description in Latvian)

Muskulatūras specifiski uzdevumi

Uzdevums[3-6]	Attēls	Apraksts	Slodzes sensoru iestatījumam
Serratus punch 4,5,6		Izejas stāvoklis: Pleca locītavā 90° fleksija. Elkoņa locītavā ekstensija. Mugura neitrālā pozīcijā, bez rotācijas vai liekšanās uz priekšu. Otra roka uz vidukļa, lai kontrolētu neitrālu jostas pozīciju. Veic: plecu joslas protrakciju/ retrakciju (katru 3 s). Bez elevācijas. 2 piegājienus līdz nogurumam. Atpūta: kad mainās kustības kvalitāte un izpildes ātrums (ekstrēmā līknes nav neitrālā pozīcijā). Atpūta starp piegājieniem: 45s – 1.5min	
Slēgtas kinētiskās ķēdes uzdevums 3,6		Izejas stāvoklis: balsta plauksta zem plecu locītavas, ceļa locītava zem gūžas locītavas, augšstilbs perpendikulārs grīdai; mugura neitrālā pozīcijā, lāpstiņas neitrālā attiecībā pret plecu joslu. Veic: plaukstas atcelšanu uz sāniem; kājas iztaisnošanu uz aizmuguri. Roka un kāja uz vienas līnijas ar rumpi. 2 piegājienus uz katru pusi līdz nogurumam. Atpūta: kad mainās kustības kvalitāte un izpildes ātrums (ekstrēmā līknes nav neitrālā pozīcijā). Atpūta starp piegājieniem: 45s – 1.5min	

3 Ekstrom, R., Donatelli, R. Soderberg, G., Surface Electromyographic Analysis of Exercises for the Trapezius and Serratus Anterior Muscles. Journal of Orthopaedic & Sports Physical Therapy, 33:247–258 (2003)

4 Yoo WG. Effect of shoulder flexion angle and exercise resistance on the serratus anterior muscle activity during dynamic hug exercise. J Phys Ther Sci. 2016;28(1):278-279. doi:10.1589/jpts.28.278

5 Castelein, B., Cagnie, B., Parlevliet, T., & Cools, A. (2016). Serratus anterior or pectoralis minor: Which muscle has the upper hand during protraction exercises? Manual Therapy, 22, 158–164. doi:10.1016/j.math.2015.12.002

6 Wright AA, Hegedus EJ, Tarara DT, et al Exercise prescription for overhead athletes with shoulder pathology: a systematic review with best evidence synthesis British Journal of Sports Medicine 2018;52:231-237.

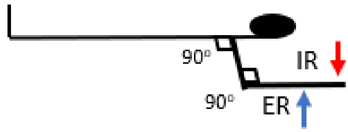
DAid smart shirt system data curves on a computer screen

Appendix 4

External (ER) and internal (IR) rotational force measurement scheme

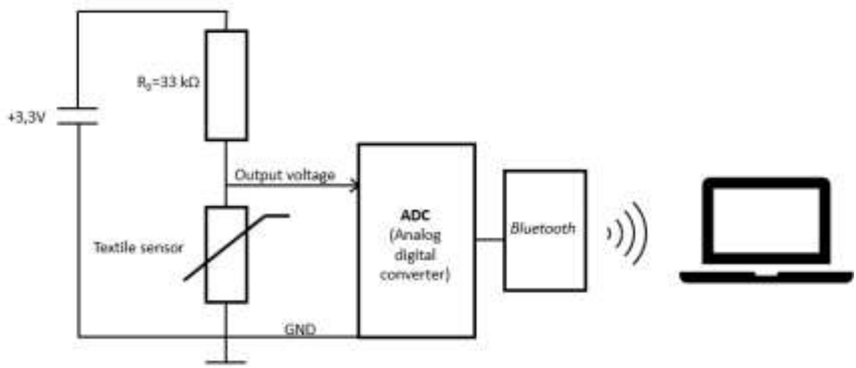
ER/IR **90/0**

ER/IR **90/90**



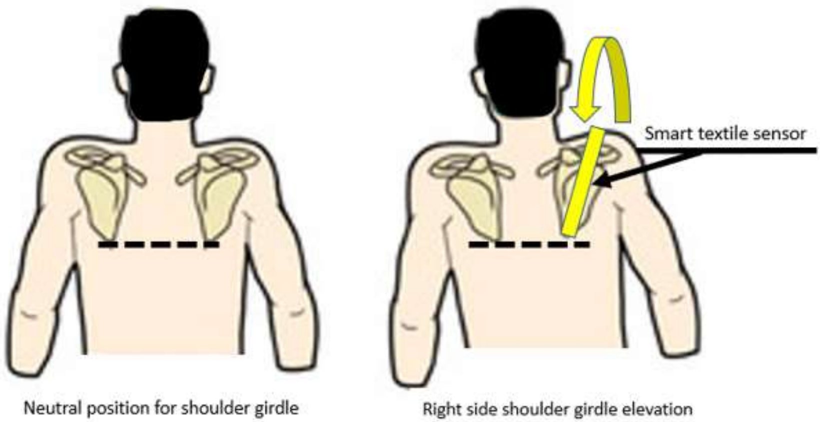
Appendix 5

Textile sensor data reading scheme



Appendix 6

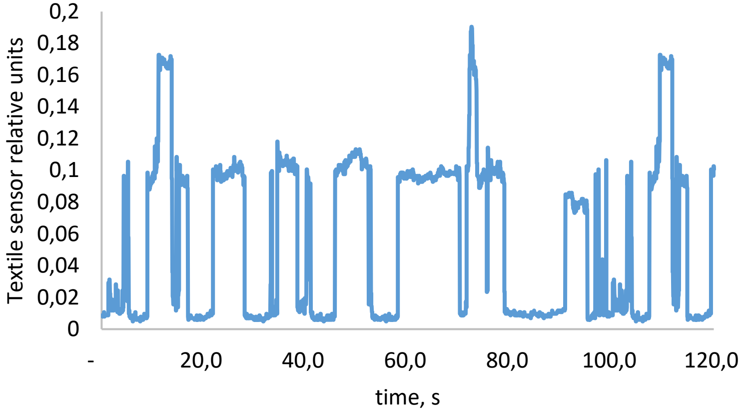
Textile sensor positioning scheme



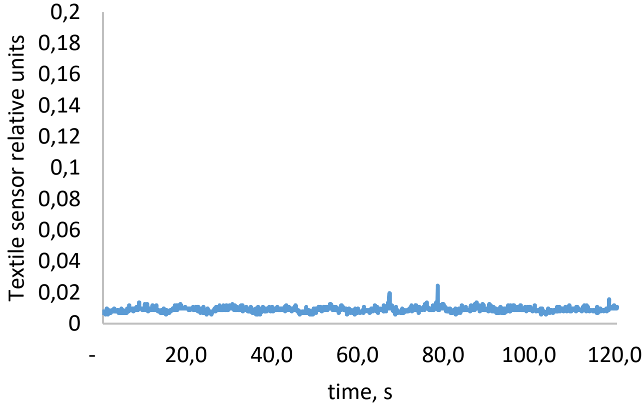
Appendix 7

DAid smart shirt prototype feedback principle

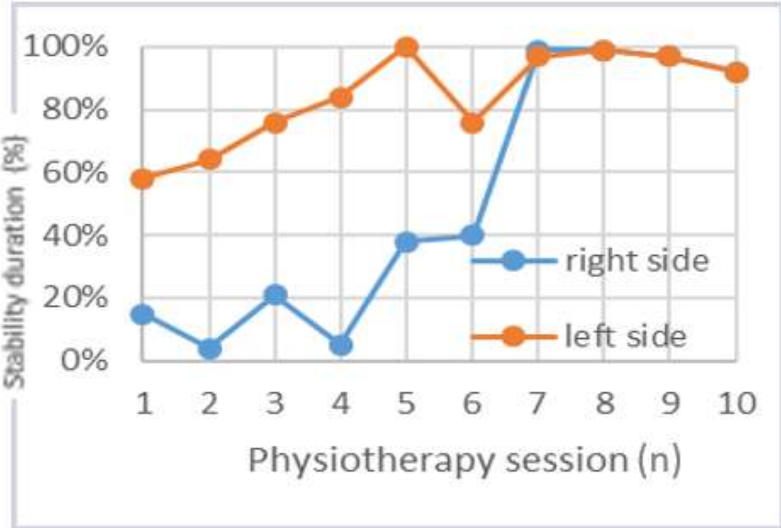
Right side shoulder girdle stability in scapular plane.
1st physiotherapy session



Right side shoulder girdle stability in scapular plane.
Last physiotherapy session



Right side shoulder girdle stability during physiotherapy exercises



Appendix 11

Elevation measurement units 95 % CI on both sides of the shoulder blade

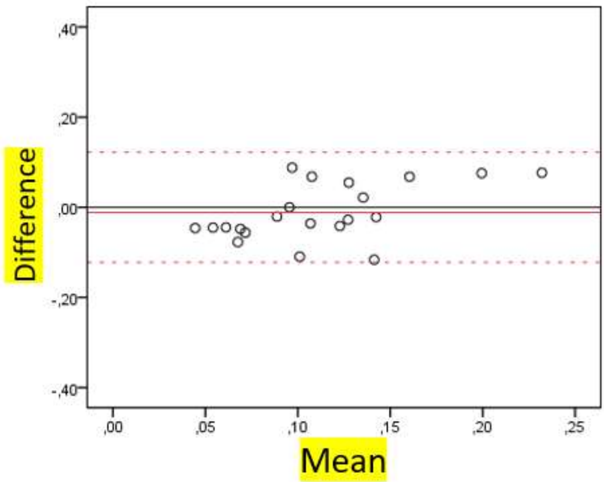
Left side measurement units 95% TI

Time interval (s)	0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8
95% CI outliers (n)	0	1	0	0	1	1	1	2	1	1	1	0	1	0	1	1

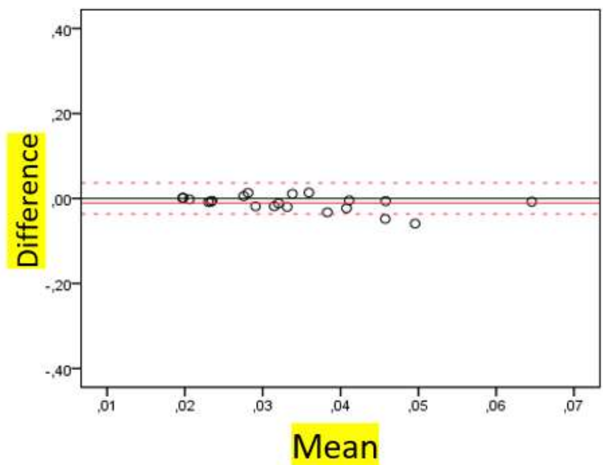
Right side measurement units 95% TI

Time interval (s)	0,5s	1s	1,5s	2s	2,5s	3s	3,5s	4s	4,5s	5s	5,5s	6s	6,5s	7s	7,5s	8s
95% CI outliers (n)	1	2	2	2	1	1	1	1	1	2	2	0	1	1	1	1

Inclusion of left-hand measurements at 95 % CI



Inclusion of right-hand measurements at 95 % CI



Appendix 13

Obtained values by groups

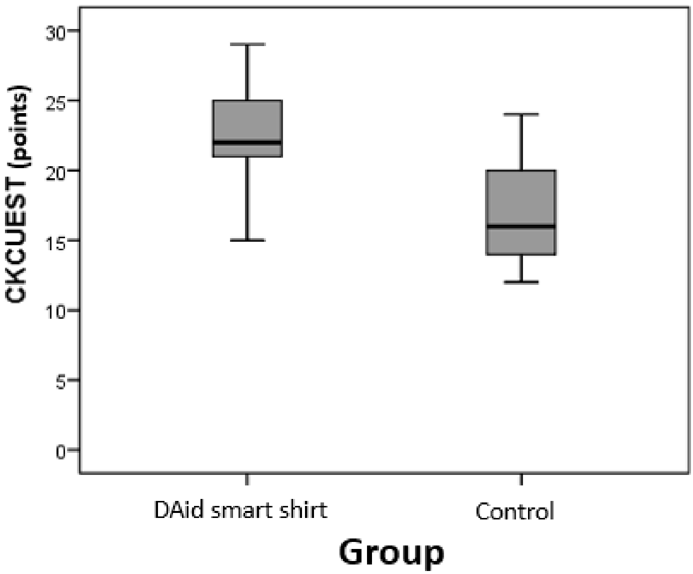
ID	grupa	DASH	DASH 2	DASH D	DASH D2	DASH S	DASH S2
18	Pētījuma	57	15	89	21	80	19
19	Pētījuma	55	17	83	20	89	18
20	Pētījuma	49	15	84	21	83	21
21	Pētījuma	55	19	86	24	80	23
22	Pētījuma	53	11	89	15	83	20
23	Pētījuma	56	19	86	17	83	19
24	Pētījuma	55	13	84	16	82	16
25	Pētījuma	57	15	88	19	82	19
26	Pētījuma	54	16	83	10	84	10
27	Pētījuma	57	18	88	15	85	15
28	Pētījuma	55	10	82	14	89	14
29	Pētījuma	53	13	84	17	85	17
30	Pētījuma	57	12	86	19	84	19
31	Pētījuma	54	15	83	15	82	17
32	Pētījuma	53.5	12	89	16	88	19
33	Pētījuma	49	19	80	17	82	17
34	Pētījuma	56	10	85	14	84	24
1	Kontroles	51	17	81	31	84	26
2	Kontroles	49	21	89	29	79	25
3	Kontroles	44	20	83	27	88	27
4	Kontroles	62	21	88	28	82	24
5	Kontroles	55	25	90	25	83	26
6	Kontroles	57	19	82	31	83	28
7	Kontroles	45	26	84	29	88	29
8	Kontroles	51	25	89	30	84	30
9	Kontroles	53	23	89	27	84	27
10	Kontroles	52	19	88	30	89	20
11	Kontroles	49	21	83	31	90	21
12	Kontroles	52	21	80	25	82	27
13	Kontroles	54	25	90	23	88	23
14	Kontroles	56	15	91	27	81	27
15	Kontroles	53	23	88	23	80	23
16	Kontroles	53	21	82	21	85	24
17	Kontroles	48	24	88	30	84	30

Obtained values by groups

ID	grupa	Roka	D 0/90	ND 0/90	D 90/90	ND 90/90	CKCUEST	dzim	vecums	KMI
18	Pētījuma	ND	0.89	0.8	0.87	0.9	16	s	54	22.4
19	Pētījuma	D	0.86	0.91	0.6	0.7	28	v	22	21.9
20	Pētījuma	D	0.95	0.89	0.87	0.84	17	s	49	22.9
21	Pētījuma	ND	0.87	0.9	0.6	0.7	25	v	41	23.1
22	Pētījuma	ND	0.98	0.95	0.85	0.79	19	s	50	23.8
23	Pētījuma	D	0.89	0.92	0.65	0.67	25	v	31	21.3
24	Pētījuma	ND	0.9	0.96	0.89	0.85	15	s	63	24.1
25	Pētījuma	D	0.8	0.92	0.9	0.89	22	s	26	21.1
26	Pētījuma	ND	0.9	0.92	0.85	0.87	21	s	29	20
27	Pētījuma	ND	0.86	0.88	0.61	0.68	25	v	50	22.8
28	Pētījuma	ND	0.87	0.9	0.6	0.7	28	v	32	23
29	Pētījuma	ND	0.86	0.91	0.58	0.68	25	v	33	21.9
30	Pētījuma	ND	0.7	0.69	0.6	0.6	21	v	54	21.8
31	Pētījuma	ND	0.85	0.88	0.85	0.88	23	s	23	22.5
32	Pētījuma	D	0.98	0.97	0.86	0.89	21	s	28	21.9
33	Pētījuma	ND	0.98	0.89	0.86	0.87	22	s	30	20.3
34	Pētījuma	D	0.86	0.87	0.61	0.61	25	s	41	19.9
1	Kontroles	D	0.68	0.75	0.7	0.65	20	s	54	23.5
2	Kontroles	ND	0.75	0.7	0.65	0.7	15	s	40	19.1
3	Kontroles	ND	0.71	0.69	0.6	0.6	16	s	28	22.8
4	Kontroles	ND	0.5	0.49	0.5	0.49	15	s	49	21.9
5	Kontroles	ND	0.6	0.6	0.5	0.5	21	v	43	22.1
6	Kontroles	ND	0.53	0.45	0.56	0.5	15	s	51	21.3
7	Kontroles	ND	0.65	0.5	0.55	0.45	16	s	34	22
8	Kontroles	D	0.63	0.65	0.75	0.64	18	s	24	22.1
9	Kontroles	ND	0.54	0.65	0.45	0.65	24	v	40	23.8
10	Kontroles	D	0.6	0.56	0.47	0.53	19	v	54	20.5
11	Kontroles	D	0.75	0.68	0.7	0.6	14	s	43	22.6
12	Kontroles	ND	0.71	0.7	0.45	0.65	21	v	50	20.1
13	Kontroles	D	0.8	0.75	0.5	0.61	20	v	43	23.6
14	Kontroles	D	0.5	0.45	0.5	0.45	19	v	44	22.1
15	Kontroles	ND	0.68	0.65	0.52	0.56	16	v	55	21.3
16	Kontroles	ND	0.7	0.71	0.6	0.59	23	v	26	22.9
17	Kontroles	D	0.7	0.53	0.51	0.49	16	s	48	22.4

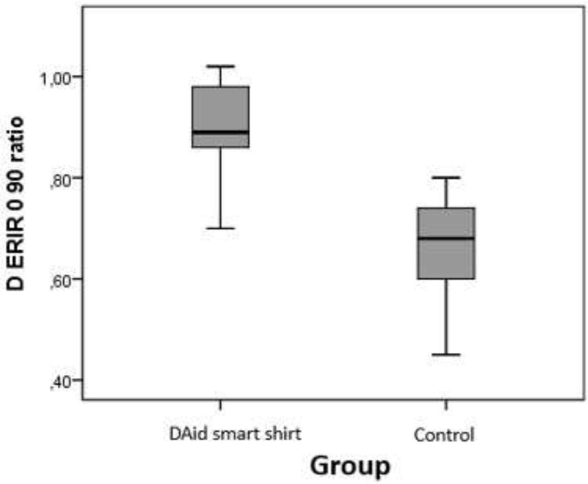
Appendix 14

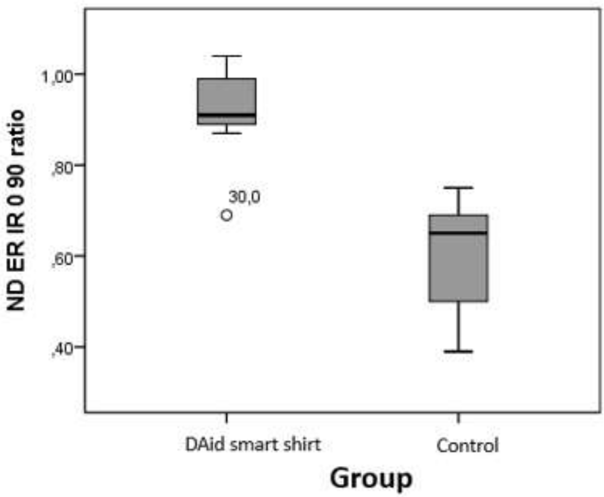
CKCUEST values after intervention



Appendix 15

Ratio values in "90/0" position dominant (D) and nondominant (ND) hand





Ratio values in "90/90" position dominant (D) and nondominant (ND) hand