CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF BIOMEDICAL ENGINEERING

Department of Biomedical Technology

Master Thesis

2022   Esra Diren

CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF BIOMEDICAL ENGINEERING
Department of Biomedical Technology

Use of Camera-Based Pose-Estimation in Telerehabilitation

Master thesis

Study programme: Biomedical and Clinical Engineering

Author of the master thesis: BSc. Esra Diren

Supervisor of the master thesis: doc. Ing. Lenka Lhotská, CSc.

Kladno, May 2022

MASTER'S THESIS ASSIGNMENT

I. PERSONAL AND STUDY DETAILS

Student's name:	**Diren Esra**	Personal ID number:	**503358**
Faculty:	**Faculty of Biomedical Engineering**		
Department:	**Department of Biomedical Technology**		
Study program:	**Biomedical and Clinical Engineering**		

II. MASTER'S THESIS DETAILS

Master's thesis title in English:

Use of camera-based pose-estimation in telerehabilitation

Master's thesis title in Czech:

Využití odhadu postury v obraze pro telerehabilitaci

Guidelines:

This thesis deals with the practical applicability of the camera-based pose-estimation approach to telerehabilitation. Create a battery of exercises, which are suitable for use with the OpenPose software, and evaluate the effect of real-time feedback on exercise performance. Select exercises appropriate for telerehabilitation with real-time feedback in mind. Perform experimental recording of the exercises. Extract pose key points and evaluate the usability of the pose estimation. Demonstrate the effect of feedback on exercise performance.

Bibliography / sources:

[1] Cao Z., Hidalgo G., Simon T., Wei S., Sheikh Y., OpenPose: Realtime multi-person 2D pose estimation using part affinity fields, IEEE Transactions on Pattern Analysis & Machine Intelligence, ročník 43, číslo 1, 2021, 172–186 s., doi: 10.1109/TPAMI.2019.2929257
[2] Hellsten T., Karlsson J., Shamsuzzaman M., Pulkkis G., The potential of computer vision-based marker-less human motion analysis for rehabilitation, Rehabilitation Process and Outcome, ročník 10, číslo 11795727211022330, 2021, doi: 10.1177/11795727211022330
[3] Ren W, Pu F, Fan X, Li S, Sun L, Li D, Wang Y, Fan Y, Kinect-based skeleton-matching feedback for motor rehabilitation: Transient performance effect of shoulder training, Journal of Mechanics in Medicine and Biology, ročník 16, číslo 3, 2015, doi: 10.1142/S0219519416500378

Name of master's thesis supervisor:

doc. Ing. Lenka Lhotská, CSc.

Name of master's thesis consultant:

Ing. Jaromír Doležal, Ph.D.

Date of master's thesis assignment: **02.03.2022**
Assignment valid until: **30.09.2023**

doc. Ing. Martin Rožánek, Ph.D.	prof. MUDr. Jozef Rosina, Ph.D., MBA
Head of department	Dean

i

<u>Declaration</u>

I hereby declare that I have completed this thesis with the topic Use of Camera-Based Pose-Estimation in Telerehabilitation independently, and that I have attached an exhaustive list of citations of the employed sources.

I do not have a compelling reason against the use of the thesis within the meaning of Section 60 of the Act No. 121/2000 Sb., on copyright, rights related to copyright and amending some laws (Copyright Act).

In Kladno, Date   …..…………..………………...

                                                                    Student´s signature

ACKNOWLEDGEMENTS

Master's Thesis title:

Use of Camera-Based Pose-Estimation in Telerehabilitation

Abstract:

The aging population and the recent corona pandemic have accelerated the need for easy-to-use and cost-effective telerehabilitation services. Computer vision-based pose estimation systems are promising for rehabilitation applications, as they enable the analysis and supervision of clients' exercises and reduce clients' need for visiting physiotherapists in person. Open-Pose is one of the computer vision based pose estimation systems that processes each incoming frame from the video to localize human body joints, also known as key points.

This study aims to demonstrate the effect of feedback on exercise performance. For this purpose, the experiment was designed in which 18 participants exercise in front of a camera and get three different visual feedback modes on the computer screen. The visual feedback was provided by the Open-Pose detection system and a special real-time application. In this study, the effect of feedback on exercise performance was shown by comparing exercises with feedback and without feedback.

The measured data was evaluated by MATLAB®, The MathWorks, Inc., Natick, MA). In addition, a questionnaire in which participants responded anonymously about their experience on the feedback application was evaluated.

Statistical differences were not found in the computed trainer and trainee distance between the feedback mode. However, the responses from the questionnaire showed that subjects were more willing to exercise with feedback.

Název diplomové práce:

Využití odhadu postury v obraze pro telerehabilitaci

Abstrakt:

Stárnoucí populace a nynější koronavirová pandemie urychlily potřebu snadno použitelných a cenově přijatelných telerehabilitačních služeb. Systémy, které odhadují pozici těla, jsou založené na počítačovém vidění a jsou perspektivní pro rehabilitační aplikace. Umožňují analýzu a kontrolu cvičení klientů, čímž snižují jejich potřebu osobně navštěvovat fyzioterapeuty. Open-Pose je jedním z takových systémů, který zpracovává každý příchozí snímek z videa, následně lokalizuje klouby lidského těla, které reprezentují klíčové body.

Cílem této studie je prokázat vliv zpětné vazby na výkon cvičící osoby. Za tímto účelem byl proveden experiment, ve kterém 18 účastníků cvičilo před kamerou a získávalo vizuální zpětnou vazbu na obrazovce počítače. Zpětná vazba byla poskytována detekčním systém Open-Pose a speciální aplikací v reálném čase. Vliv zpětné vazby na výkon cvičícího byl následně prokázán po srovnání výsledků, kdy účastníci prošli jak cvičením, kdy dostávali zpětnou vazbu a kdy nikoliv.

Naměřená data byla vyhodnocena pomocí programu MATLAB®, The MathWorks, Inc., Natick, MA) a dotazníku, ve kterém účastníci anonymně odpovídali na své zkušenosti s aplikací zpětné vazby.

Získané výsledky potvrzují, že mezi jednotlivými variantami zpětné vazby nebyla nalezena statistická významnost v metrice vzdálenosti keypointů mezi cvičícím a cvičitelem. Avšak odpovědi z dotazníku ukázaly, že dotazovaní byly ochotnější cvičit se zpětnou vazbou.

Klíčová slova:

Open-Pose, telerehabilitace, bez markerů, analýza pohybu, sledování těla, zpětná vazba v reálném čase, odhad polohy člověka

Table of Contents

List of symbols and abbreviations

CV   Computer vision

EMG   Electromyography

MoCap   Motion Capture

IrMoCap Infrared Marker Based Motion Capture

ToF   Time-of-Flight

NN   Neural networks

Ex   Exercise

List of Figures

List of Tables

1 Introduction

Regular physical activity makes people more energetic, and increases their well-being, life quality. Physical activity is defined by the contraction of skeletal muscle that produces bodily movement and needs energy. Exercise refers to a physical activity that is planned and is executed with the goal of attaining or maintaining physical fitness. Having a physical activity by practicing exercises are associated with numerous physical and cognitive health benefits for men and women.

Science indicates that regular physical exercise training has many beneficial effects on cardiorespiratory, resistance, flexibility, and neuromotor exercise training beyond activities of daily living to improve and maintain physical fitness and health is essential for most adults [1].

Exercises are also prescribed in a therapeutic approach to correct impairments, restore muscular and skeletal function, and/or maintain a state of well-being [2]. In fact, it is important in some cases to prescribe exercises, not to fall in a vicious circle characterized by diminishing physical activity and muscle strength and an increase in illness and sick-role behavior. Rehabilitation centers and hospitals plays an important role in order to break this cycle and improve physical condition.

Conventionally, patients execute rehabilitation exercises under physiotherapist supervision [3]. However, exercise training in clinical settings is a long-term process that needs vast therapist resources and considerable time and money. And also, it may require additional exercises at home to increase the benefits of the therapy [4].

On the exercise side, coaches or personnel trainer's tracker one's exercise and assist to improve performance with timely feedback. Also, monitoring user's movement by instructors during the exercise and providing correct feedback prevent some potential injuries during session. However, exercise trainers like rehabilitation therapy are not affordable or accessible to everyone and it is impossible for physiotherapist to see their patient everyday [5].

Therefore, several special systems and methods have been developed to allow patient to do their rehabilitation from home while still having feedbacks on their movements. Using telerehabilitation systems make it possible in-home rehabilitation. As an alternative way, the home rehabilitation system should be easy to use low cost to allow the patients to practice more while still being monitored/supervised [6].

2 The State of Art

A marker-based system can be an alternative for telerehabilitation systems. It is used for in-home rehabilitation to recognize patient's movements by placing markers on their bodies. However, it requires the correct placement of the markers on the body by a professional. In fact, if the markers are misplaced, it might cause an inaccurate detection. Moreover, it is not a comfortable to keep many markers attached to the body for long hours during the exercise. And these marker-based systems are expensive [7]. Due to the high cost and difficulties of the marker-based system, other types of telerehabilitation systems are also being developed.

Microsoft Kinect has great potential as one of the marker-less human motion capture system for home-based exercise training. It is a camera-based sensor able to detect accurate gesture and capture motion. Also, it provides a skeleton-matching feedback system which can clearly show differences between a user's actual exercise movements and reference exercises in real-time [4]. However, Microsoft Kinect requires patients to purchase the sensor, which is a cost for users [7].

Computer vision-based human pose estimation is a variant of a marker-less telerehabilitation system with the advantage to only use a laptop or mobile camera. Thus, this CV-based telerehabilitation eliminates the need to purchase any additional device or sensor for performing human motion analysis and enhances feasibility for use in exercise training [8].

Alpha-Pose, Open-Pose, and Deep-Pose are CV-based pose estimation systems that process each incoming frame from the video to localize human body joints, also known as key points. All of them are real-time multi-person systems to jointly detect human body, hand, facial, and foot key points. These systems enable patients to perform exercises at home using an ordinary webcam. When the trainee performs the exercises, they only need to stand in front of their

laptop or mobile camera to allow CV-based systems to detect their skeleton movements. The incoming video stream from the camera, smartphone, or webcam is provided to the pose extraction module [5] Thus, it is possible to measure whether the athlete's actions are in expected location, the key points of the performed exercise are extracted to compare with the ideal action with the use of human motion recognition systems [9].

Sum up, there are several special systems and methods have been developed to allow patient to do their rehabilitation from home. OpenPose software is the one of the human pose estimation systems. The advantage of the OpenPose system is only to use a laptop or mobile camera and there is no need to purchase any additional device for performing human motion analysis. But still, it may be complicated to exercise with OpenPose or other motion capture systems because of the lack of motivation and not knowing how to exercise correctly.

Therefore, the best way would be to practice at home while still being monitored and receiving feedback on the way of practicing different exercises. Real-time feedback application could be a real advantage for home rehabilitation. OpenPose can extract body key points and their confidence to create real-time feedback.

Studies have been conducted to show the impact of feedback on telerehabilitation. However, in relation with the past research, there are only few studies that creating real-time feedback with using OpenPose [5] [8]. For this reason, this study will be performed with the real-time feedback is provided by OpenPose. The aim of the study is to find out if people are exercising better with feedback.

2.1 Overview of Movement Analysis in Rehabilitation

Movement analysis is often performed to determine the source of discomfort, immobility or injury. After assessment, a physical therapist likely compiles a report to deliver to the referring physician. If physician does not request movement analysis, the patient is usually focusing to enhance exercise performance. Analysis of movement is a clinical assessment and most often one is gait analysis. There are a variety of technology including force measurements, 3D computerized analysis, video and EMG equipment. They can assist a physical therapist collect comprehensive data about a patient's movement.

The one of the movement analysis method, clinical gait analyze is the process of recording and interpreting biomechanical measurements of walking. It supports clinical decision making in case of gait dysfunction. During the appointment, patients are required to walk the length of a 10-m walkway a minimum of ten times. Also, patients are supposed to cooperate with therapist over an appointment lasting up to two hours. And other measurements such as kinetics and dynamic polyelectromyography might be used for more in depth [10].

There is various equipment that is available for analysis of human movement. In 2D video analysis, high quality video footage of frontal and side views is included in clinical gait analysis. Video provides a record of the overall patient gait style and functional ability. In 3D computerized analysis, marks are placed on the legs and pelvis. Their positions are recorded by cameras as the patient walks along a walkway. The limb segments and the angles at the joints (kinematics) can be calculated from the 3D position of the markers. The results from subjects with gait disorders can help diagnose the problem and decide a treatment. In force measurement, this method is measuring the force applied to the floor during walking. One or more force plates are embedded in the floor of the walkway. Also, it is possible to obtain a biomechanical model by combining force measurement with the 3D information. This can be used to find the moments and powers (kinetics) acting at the joints. And muscle activity and energy cost can also be measured by electromyography (EMG) equipment. During walking, surface electrodes record muscle activity. Information of energy consumption can be provided with measurements of oxygen consumption or heart rate [11].

After diagnosing the motor disabilities, the doctors or physiotherapists plan a therapy program for the patient. Therapy sessions is often performed several times in a day or week. Based on the patient's progress, it can be determined in regular intervals. Treatment may proceed for several weeks based on the patient's recovery. However, concerning the limited staff at hospitals and prolonged time period for rehabilitation, continuing the therapy in home is very helpful. Also, frequent treatment in a therapist's clinic is expensive. Therefore, in-home therapy can be a good option [12].

2.1.1 Accelerometers

Accelerometers are often used as motion sensors-based technologies by estimating the limb kinematics and posture. Accelerometer is a type of positional sensor which is based on Newton's second law (Force = Mass × Acceleration). And it is operated by measuring acceleration along the sensitive axis of the sensor. A proof mass excited in a mass-spring-damper system is used as a detecting method by most accelerometers as shown in (figure 1) [13].
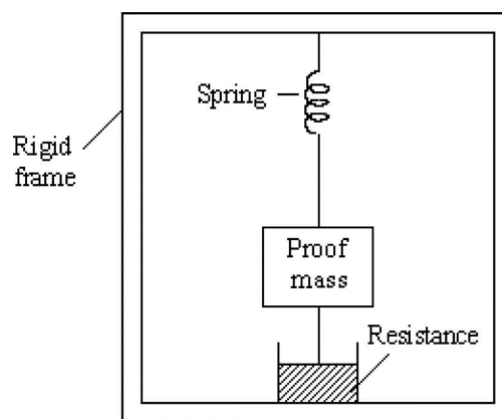
Figure 1: Basic layout of accelerometer [13]

There are three common types of accelerometers, piezoelectric, piezoresistive and capacitive types. All three types of the accelerometers have the same basic principle of the spring mass system.

Piezoelectric accelerometers include a piezoelectric element with a seismic mass. The acceleration of the sensors causes the seismic mass piezoelectric element to bend. This change causes a displacement charge to occur on one side of the sensor. And the results in a variable output voltage signal that is proportional to the applied acceleration.

Piezoresistive accelerometers are typically produced from a surface micromachined polysilicon structure. On this sit polysilicon springs, the electrical resistance changes when the acceleration forces are applied. And again, the acceleration and the resulting voltage are proportional. These accelerometers are useful for receiving vibration information at low frequencies.

Differentiable capacitor accelerometers run on the principle of change of capacitance is proportional to applied acceleration. They utilize a differentiable capacitor with central plates

attached to the moving mass and fixed external plates. The applied acceleration makes the capacitor disequilibrium. And this results in the output wave for the accelerometer [14]. Mostly, the capacitive accelerometers have higher sensitivity, stability and resolution than piezoresistive accelerometers. And they are suitable for measuring human posture [13].

There are several techniques that employed a set of accelerometers to monitor the human motion information for a home-based rehabilitation system. Also, some of them propose wearable garment rather than attaching to the human body [15] [16]. Considering some aspects for deciding to use this technique may be important. For financial aspects, it requires multiple sensors on the human body to detect the motion information at different joints. Also, the installation and calibration may be cumbersome in the absence of a technical person [12].

2.1.2 Optical Motion Capture

Optical motion capture (MoCap) systems can be divided into marker-based and visual markerless systems. Both techniques base on computer vision techniques for extracting movement features and monitoring body parts. The marker-based system can be classified into active marker-based and passive marker-based systems. Both active and passive marker-based systems utilize multiple cameras set ups to monitor the marker's location to extract the joint's spatial position as given in (figure 2). The preferred active and passive marker-based motion capture systems are PTI-PHOENIX and VICON, respectively. These kind of sophisticated MoCap systems detect movements with reliable accuracy with some disadvantages [17].
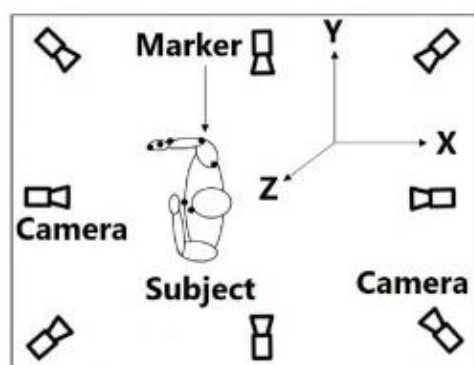
Figure 2: Marker-based motion capture [17]

The active marker-based system uses infrared emitting points (markers) for motion capture. The technique is called optical infrared marker-based motion capture (IrMoCap). This is relied

on a group of cameras, typically no less than 6, surrounding the person(s)/object(s) to be monitored.

The light emitting markers and is detected by the cameras. Markers are positioned in the body of a person. The location of the markers is then triangulated. Through triangulation techniques the system computes the absolute position in space with submillimeter resolution and at speeds above 500 Hz. And then presents as an image with the use of computer software [18].

Vicon system [19] one of the most popular techniques for the marker-based motion analysis uses retroreflective markers, which adhere to the body's bony landmarks for motion capture as a passive marker-based system [20] [21]. Motion capture space involves an area which the capture volume surrounded by a number of high-resolution cameras. Recording of the subject whose motion is to be captured is performed from each camera. The subject carries a number of reflective markers attached to their body, in triangulated positions. When the subject moves through the capture volume, infrared light is reflected back into the camera lens and strikes a light sensitive plate. So, a video signal is created. The Vicon data station synchronizes in time all the cameras and collects the video signals in central computer on which the Vicon software suite is installed [22], see Figure 3.
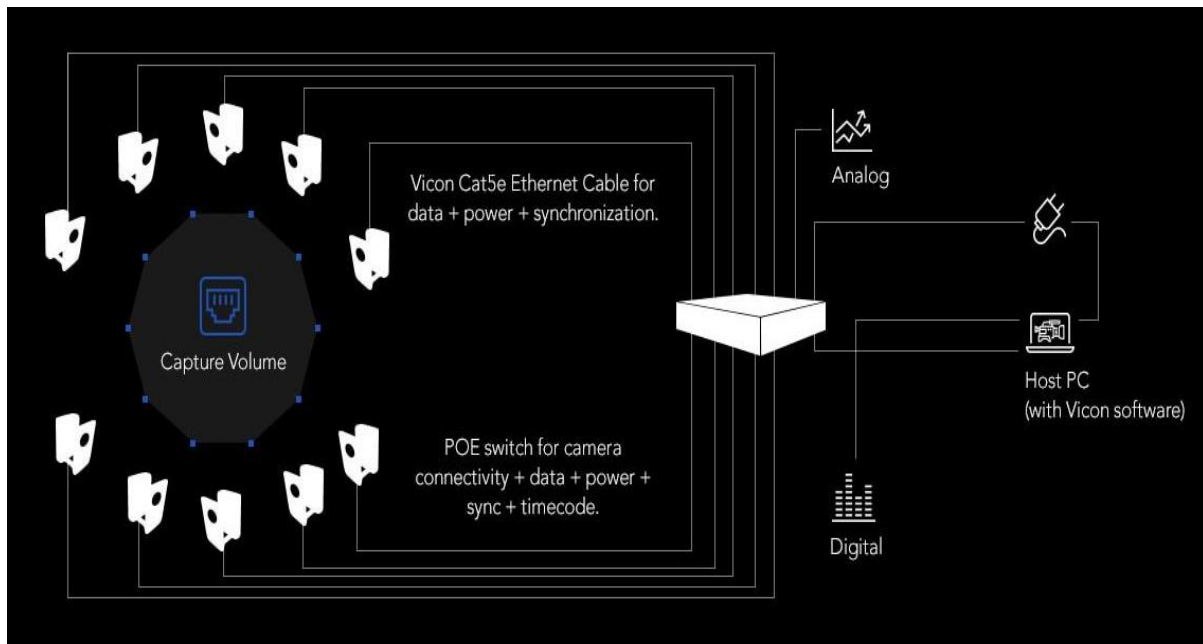
Figure 3: Structure of the Vicon motion capture system [19]

As an advantages of the optical MoCap systems the user can move freely due to there are no cables attached to a computer. This allows motions in a large volume and monitors of more users at once. Moreover, the data are very clear and detailed with this system. The main

7

problem is the interference. The user can sometimes cover the markers or if the light reflected from a specific marker has an insufficient intensity, it can lead to inaccuracy of the output. Another disadvantage is these systems require professionals for laborious tasks associated with marker placement and calibration restricting their utility in the home and clinical environments. And mostly the cost of the equipment for the optical MoCap systems are very expensive [22].

2.1.3 Microsoft Kinect Sensor

Kinect is a 3D Motion-sensing camera that monitors and evaluates multiple movements and gestures. Also, it functions in image recognition, microphone input, voice recognition, community interaction, and human-face recognition. Microsoft Kinect is presented as a low-cost motion tracking 3D camera for Xbox game consoles in 2010. 3D Kinect sensor and its integrated body tracking abilities have triggered an important amount of research on human motion analysis, rehabilitation and clinical assessment [17].

It includes a visual and a depth sensor, which provide color and depth information of the captured scene, respectively. This helps to construct a 3D view of the environment. Moreover, the depth sensor of the Kinect skeleton information of the human and its tracking in the video can be used to encode the respective motion information of the joints [12].

The recognition and tracking function of the Kinect contains four main parts infrared camera, infrared projector, RGB camera and multi-array microphone. The infrared projector reflects infrared spectra to irradiate the person for random reflection points read by the infrared camera in order to create a visible depth map of people and objects, and then determine human action. Furthermore, the RGB camera can capture a video image in the field of view and assist calibration of body movements meanwhile the microphone array of four microphones captures sound and filters out background noises to locate the sound source and recognize speech [23].
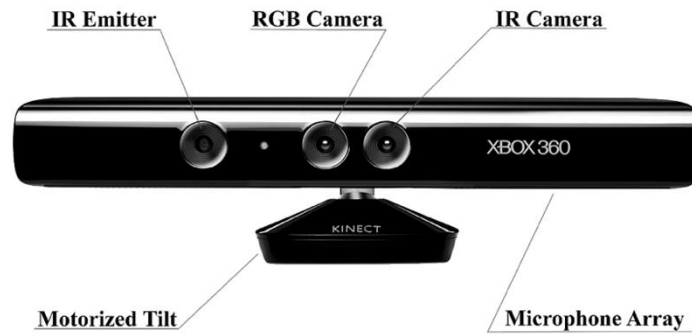
Figure 4: Components of the Microsoft Kinect motion sensor

Kinect has two generations so far. The first generation of the Kinect sensor (Kinect v1) was launched for the Xbox 360 game console in November 2010. The second version of the Kinect sensor (Kinect v2) was presented officially in the summer of 2014 [24]. The core of the Kinect v1 camera contains a light (SL) sensor (PrimeSense, 2010) with 320 x 240 spatial resolution. Kinect v2 utilizes 0.13 μm system-on-chip Time-of-Flight (ToF) sensor with 512×424 spatial resolution that is maximum for ToF-based 3D cameras. The ToF technology has enhanced the quality of data acquisition of Kinect v2 by providing maximum spatial resolution for the depth images and developed skeletal tracking performance. Hence, it became a proper and low-cost sensor for indoor and outdoor environments [17].

In healthcare, physical rehabilitation exercises, medical operating room assistance and fall detection and prevention applications are performed with the Kinect technology [24]. An interactive game-based rehabilitation tool has been developed for balance training for adults with neurological injuries [25]. A motion and angle extraction device has been developed for patients with upper extremity impairment by integrating Kinect and a smart glove [26]. An interactive rehabilitation system was proposed for disabled children. This system uses Kinect to record rehabilitation exercises done by a physiotherapist or a disabled child [27].

2.2 Feedback

There are some researches that demonstrate the effect of feedback on the patient while performing the exercise using pose estimation systems [4] [28].

In the first study, feedback are provided by Microsoft Kinect. There are two feedback modes in the Kinect as the skeleton-matching feedback mode and the mirror feedback mode (figure 5). According to the skeleton-matching feedback, the differences between the trainer's motion and the instructor's motion are provided by the skeleton-matching feedback mode. In this mode, feedback looked like two skeletons, the reference one is drawn from the instructor's motion that is prerecorded and the one is drawn from the trainee's motion which is updated in real-time. And these two overlapped on the screen. Thus, trainees can control the position and rhythm [4].

(a)   (b)
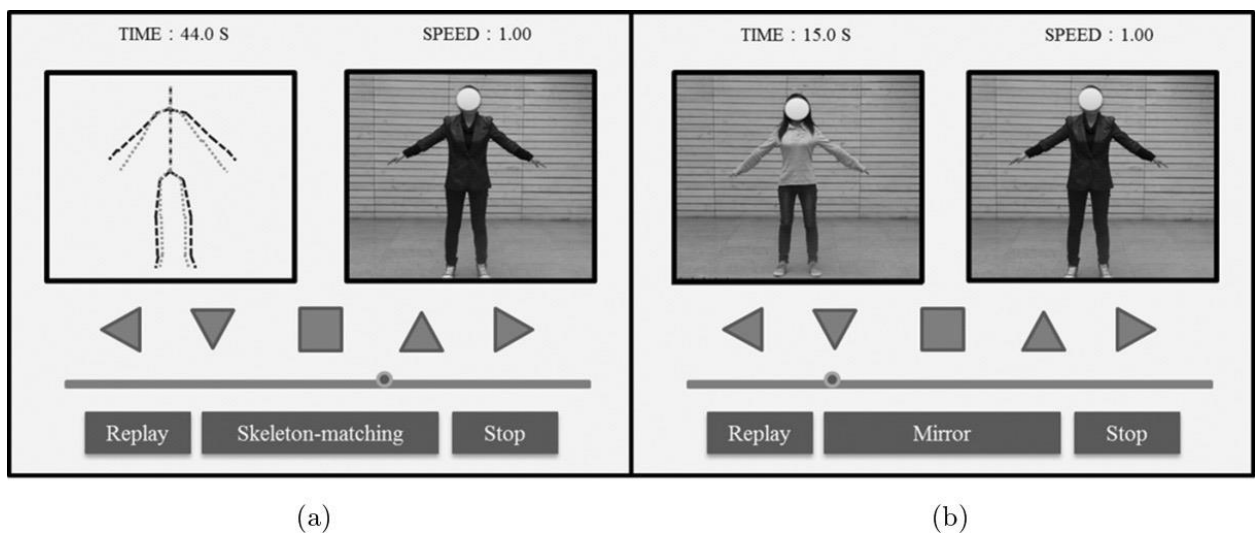
Figure 5: Feedback mode: (a) Skeleton-matching feedback mode and (b) mirror feedback mode [4]

The study compared the skeleton-matching feedback with the mirror feedback mode which is for the control part of the study. This mode provides a mirror image of the trainees in real-time to let them adjust their motions. The result of the study verified Kinect-based skeleton-matching system can help for training performance. Visual quantitative differences with instructed motion can clearly be displayed with real-time skeleton feedbacks. But the mirror feedback mode only offers a mirror image of the trainee's motion, and it doesn't provide a real-time overlapping comparison [4].

Another research about the real-time feedback is provided by Open-Pose. This study has developed a yoga training system based on real-time pose estimation. The method of the study composed of the pose estimation model based on Open-Pose, correction algorithm module, standard action data-base module, interface system. In the part of the correction algorithm

module is used for detection the difference between position of reference data and the current position of the subject. Inputs are provided from the standard yoga pose library as a reference and the subject's current position from video stream. After having the input from the video stream and detecting the key points, correction algorithm module calculates difference between the two-position information. And then, algorithm evaluates whether the current yoga action is correct or not.

Mostly, main parameters for feedback are distances and angles to obtain the accuracy of the action. For example, "keep your arms bent at 90 degrees", "the distance between your arms and shoulders is the same width". Basically, the degree of bending of the arm and the distance between the two legs are crucial to the judgment of the correctness of yoga movements. After all the action conditions are met as related to the feedback of the motion, the action can be count as an ideal. Otherwise, according to feedback the subject is required to make corresponding corrections on her/his body position. And as shown in the Figure 6, the feedback is displayed as a text in the user interface. It is divided three parts. The middle part and the right part are used for action teaching come from the standard posture library, on the left is used for real-time return results of the correction module [28].

Figure 6: User Interface [28]

As mentioned in the last two research papers, it is important to ensure that the subject maintains the correct position while performing the exercises. The type of feedback used may vary according to the researcher's request. There are feedback forms that skeleton matching, in text form, audio form, or graphical type on the video stream.

3 Aim of Thesis

The aim of this study is to demonstrate the effect of visual feedback on exercise performance. For this purpose, I will design a study in which participants will exercise in front of a camera and get realtime visual feedback on the computer screen. In this study, the effect of feedback on exercise performance will be shown by comparing exercises with and without feedback.

I will create a database of exercises recorded by RGB camera, extract the pose keypoint and evaluate usability of the pose estimation for the given exercise.

I will use subjective and objective evaluation in order to select the most suitable exercises according to the visual feedback and OpenPose software.

I will perform the user study, evaluate a questionnaire, and perform objective analysis with matlab to find out if people exercise better with feedback.

The project will continue with further analysis of the recorded database and the performed study.

This work is a part of a team research project on human motion analysis. Therefore, in the appendix I will state what parts of the project I have solved and what parts were solved by other team members.

4 Methods

4.1 OpenPose

This study is based on OpenPose body detection algorithm. It is Open-Source Software which is included in the OpenCv library. And it is free for non-commercial use [29]. The system is easy to use, doesn't need a laboratory setting or technician. It only requires a regular video camera that is already integrated most common electronic devices such as smartphones, laptops, or smart TV's. Also, one of the other advantages of using the system is that the detection of motion is possible even from any regular RGB video. This means that there is no problem to use existing video recording to evaluation [30].

It is one of the most commonly used software tools for pose detection. Artificial intelligent methods are used to work this software as like other CV-based pose estimation systems. Neural networks (NN) trained on annotated images [31].

OpenPose is a real-time system feature points which are coming from body, foot, hand, and facial points to detect on single image. The total amount of feature points is 135. It can detect multiple body key points (25 points), hand key points (21 points), and face key points (70 points) [32] [33]. Recording the subject's motions are possible by using one or two video cameras to analyze motion of limbs [34] In this study only one camera is used to detect users motions with the body key points.

The OpenPose system allows evaluation of body movement from the recorded video of the user. The system uses the 25 body keypoints to analyze the video. Every keypoint corresponds to the certain anatomical point of the human body (figure 7). After processing of the video by Open pose, it is returned the x,y coordinate values and the detection confidence for each of the body key points for each frame [30]. Those keypoints are then saved in a file and can be used in the application to calculate angles, distances between keypoints.

Regarding to evaluation of useability of OpenPose system; quality of detection based on the keypoint confidence values are resulted by the OpenPose. The confident interval is from zero

to one. It means that if the keypoint can't detected, the confidence value is zero [30]. And using a simple calculation it is also possible to calculate the percentage of missing points in x and/or y coordinates.

4.1.1 Body keypoints

There are 25 body keypoints (figure 7). It contains ears, eyes, nose, the center point of the shoulders and limb joints which are shoulder, elbow, wrist, hip, knee and ankle. And they are used for the purpose of detecting the location of limbs [32] [29].
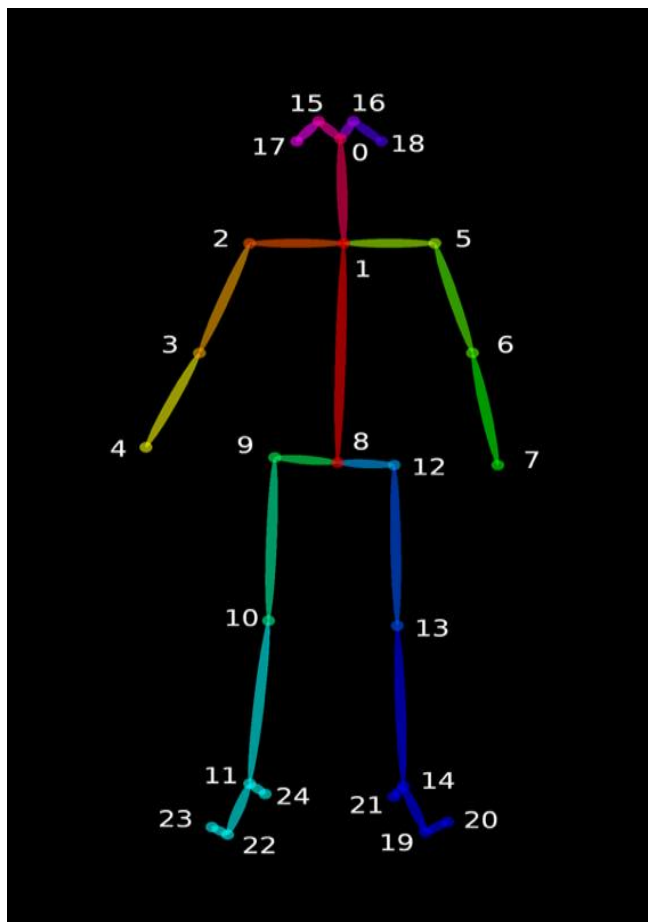
No.	Name
0	Nose
1	Neck
2	Right shoulder
3	Right elbow
4	Right wrist
5	Left shoulder
6	Left elbow
7	Left wrist
8	Mid Hip
9	Right hip
10	Right knee
11	Right ankle
12	Left hip
13	Left knee
14	Left ankle
15	Right eye
16	Left eye
17	Right ear
18	Left ear
19	Left big toe
20	Left small toe
21	Left heel
22	Right big toe
23	Right small toe
24	Right heel

Figure 7: OpenPose 25 keypoints for body detection [29] [35]

4.2 Selection of exercises

PhysioTools is a database of exercises that is performed by professional trainers as a video aid for exercises in the home environment. It is a very comprehensive exercise library. For this reason, the study of the exercises were selected from the PhysioTools [36]. And in this study two things are considered in order to select the exercises which are OpenPose system and visual feedback. Concerning OpenPose, the exercises should be suitable to estimate the human pose. And for the feedback, exercises should be slow enough to follow it on the screen.

There is a study that presents the possibilities and limitations of current camera-based systems in telerehabilitation. It demonstrates the effect of the camera views and position of the trainees on the detection of keypoints. The study evaluates the efficiency of OpenPose use on video recordings while people exercise in front of the camera. And human position detection is captured by only one RGB camera. The results demonstrate that greatest effect on the detection of keypoints is the position of the trainees. Standing position and sitting position come out as the most detectable instead of lying position and position on the knees. And the effect of the camera view doesn't show big difference. But in front view has better quality of detection results compared to side view [30].

Therefore, in my study, the selection of the exercises was done consider of this study for OpenPose. Around 100 physiotherapy exercises were selected from the physiotools data base. Exercises were evaluated if the exercise could work with the application or not and 71 exercises left. They were recorded.The exercises selected are mostly with a standing position and/or a sitting position and in front view. Regarding to the selection of the exercise, visual feedback is the other essential thing.The exercises were performed slowly while recording the video. Because the user should be able to easily follow the visual feedback on the computer screen during the exercise. And the final decision for the exercises to be used in the experiment was made with the opinion of the physiotherapist. Three exercises were selected that were most suitable for rehabilitation and the system.

4.3 Exercise evaluation

Critical points were selected from the each exercise videos, as you can see Table 7 in appendix. They are different and depends on the aim of the exercises. These are indicates some angles and relative distances between the body keypoints. The numbers are body keypoints numbers, please see Figure 7.

They are also used to show the important features in the visual feedback.Thus, users can pay attention to these body segments to perform their performance properly.They are seen as a red lines in the skeleton-matching feedback (figure 11).

These are significant because another metric could be a calculation of the angles and distance between these key points to show if exercises are performed with feedback differ from exercises without feedback. This part of the study will be used to evaluated the exercise in the future.

4.3.1 Exercise preparation

After the exercises were selected, these exercises were started to be recorded with the RGB camera to make a database of videos. And then the videos were made with OpenPose. And the key points were extracted to be able to evaluate usability of the pose estimation. For this, OpenPoseDemo was run over all the videos. About this process; windows .bat file was used to run OpenPose over all the videos. Related command is written in the .bat file.

And the .bat file was put to the folder with videos. The .bat file was run from command line. As a result, Json files and the videos with OpenPose were obtained for each exercise (figure 8). The videos with OpenPose means creating videos with detection of key points. Videos have OpenPose skeleton for each frame. And Json files are obtained for the next step which to create mat file.

Figure 8: Video with OpenPose skeleton for each frame

4.3.2 Subjective evaluation

Subjective evaluation was included that after obtaining all videos with skeleton, watching the records again since considering camera views, position of the trainees and speed for the feedback. It means watching them feasibility of OpenPose system and the feedback in mind. And videos was evaluated in a table with the names of all exercises if it is from front view for OpenPose and if it is slow enough for the feedback (table 7).

4.3.3 Objective evaluation

Objective part of the evaluation was about doing some calculations to determine usability of the pose estimation in MATLAB. And the calculations are required to use the mat file which has x, y coordinate values and the confidence values of the keypoints for the exercises.

```
1
2    %%percentage of missing points;
3    percentageofmissingpoints = sum(isnan(xbody(:)))/length(xbody(:))*100;
4    %%mean confidence;
5    meanconfidence = nanmean(cbody(:));
6
```

Figure 9: Equations for the calculation in Matlab

The process of obtaining the mat file for each exercise was that using the Json files which was obtained from the previous step. The Json files are converted to the mat file by another script. The script take the folder with Json files as input and return the mat file.This step that converting the Json files to mat file was performed for all the videos by using a for loop. And final results for each exercise were saved in a table with the name of the exercise, the percentage of missing points, the mean confidence (figure 9), and the conclusion if the exercise could work with OpenPose and with the use of feedback (table 7).

4.4 Exercises

Three physiotherapy exercises were selected for the user study together with physiotherapist (figure 10). They are the most suitable to use with the application. These exercises were recorded by the trainer properly.

1. Hip Abductionin Standing (HASL)
2. Symmetry Abduction (SA)
3. Single Leg Squat (SLS)

ex1(HASL)   *ex2(SA)*   *ex3(SLS)*
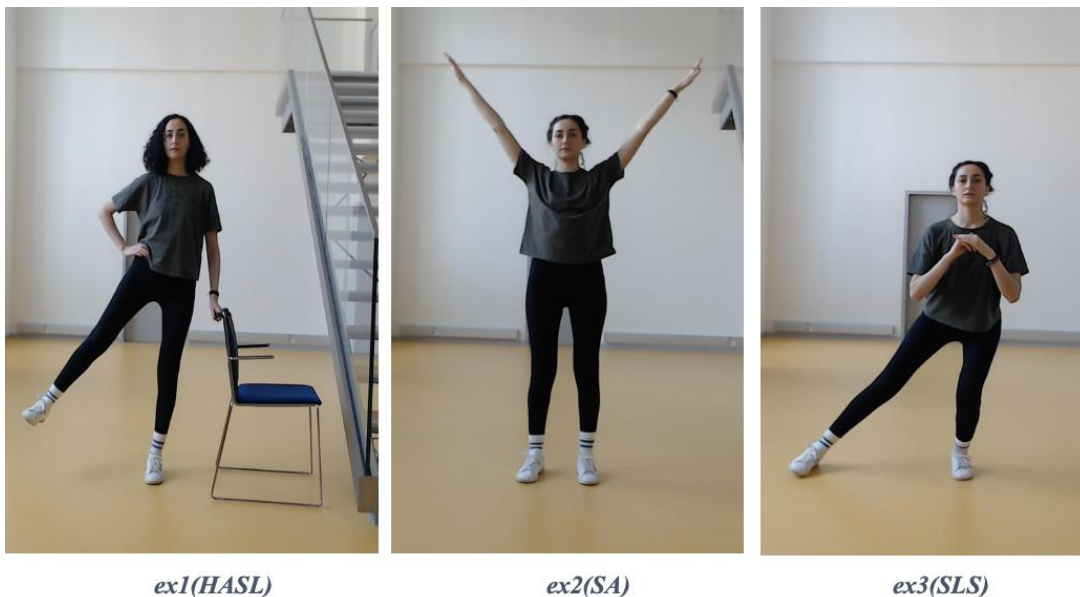
Figure 10: Three physiotherapy exercises for the user study

The exercise videos were loaded to the application and the written and oral instructions are prepared based on the exercise videos and on the frames. The instructions were stored in a text file (figure 11).

These text file were prepared for each exercise independently. It involves several information: the first line is used to plot the most important segment of the skeleton in red to help the patient to focus on the most important part of the body to execute properly the exercise.
For example, if the torso, the neck, and the head are wanted to highlight, the first line should include; 0,0-1,1-8 (0 for the head, 0-1 for the line between the key points 0 and 1 that represent the neck and 1-8 for the line between the key points 1 and 8 that represents the torso).

The second line is composed of the number of the frame from which the program is supposed to show and say the instructions. The line contains the instructions, and from which frame it should be plot on the screen and the number of the last frame as well. For example, 50:" Please, raise you right hand";200:" Please, put down your right hand";500:" Please, raise your left hand";*the last frame number*:"end".

```
1-2,2-3,3-4,1-5,5-6,6-7
131:'up';330:'down';536:'up';708:'down';933:'up';1090:'down';
1338:'up';1548:'down';1780:'up';1956:'down';2149:'end'
```

Figure 11: The symmetry abduction exercise text file used for written and audio instructions

4.5 Real-time application

The real-time feedback application contains two main programs. The first one is only used to create new exercises to add in the data base of the telerehabilitation application. And the other program works with the first program's inputs and it is possible to create feedback (skeleton mode, audio mode, text mode etc.) with by using the program. Basically, the application is developed using by OpenPose software and "the real-time feedback" is created using by the application.

Trainer records the exercise for the users. It is the reference video for the visual feedback. Trainers should put the reference video in the application to be processed. When the trainers runs the application, OpenPose is run by the app and then all body keypoints of the reference

video are detected and printed for each coordinate (x, y) and each frame into three types of files: mat files, NumPy files and each frame with the skeleton in several jpeg files (figure 8). After this process, the application is ready to use by the user. User should start the application. Screen will be separated into two parts. On the right side, there will be visual feedback and on the left side it will present real time vision of the trainer.

After running the application, user should find the right position to start the exercise. This is done to equalize the height difference between the trainer and the user. There are red circles on both skeletons to match them (figure 12). After matching, the application optimizes height difference. So, both skeletons are shown as same size on the screen.

Then the exercise starts and is shown with the blue skeleton for the skeleton-matching feedback mode. But before blue skeleton starts to show the exercise there is a few seconds to let the user find his/her position. The user should adjust his/her position where both skeletons overlap on the screen before to start doing the exercise (figure 13). This will help the user to exercise synchronically with the blue skeleton (figure 14).

Apart from the skeleton feedback mode, there are two more feedback modes. It is possible to switch to them with the space key and in the program. Finally, when the exercise is finished the feedback screen will disappear. And user can go for the next exercise or if it is finished, they can close the application.

4.6 Feedback in application

There are two skeletons as feedback for the skeleton-matching feedback mode. One is blue skeleton which is coming from the reference video which is recorded by trainer and the important segments of the skeleton according to the exercise are showed in red color to help the user. And the other one is a green skeleton made from the users' keypoints from the camera and in real time during the exercise and displayed on the screen.

There is also an option that allows the user to switch the right screen from the skeleton feedback to the real-time vision of the user by pressing the space bar of the keyboard (figure 15). This option will be used to change the feedback condition from the skeleton-matching feedback mode to the mirror mode. And it is possiple with the same way to change the feedback mode to the mixed feedback mode (figure 16). Moreover, to make it easier to follow the exercise on the screen. There will be other feedback. Instructions will be presented as aloud guidance and as a text on the screen during the exercise (figure 14).
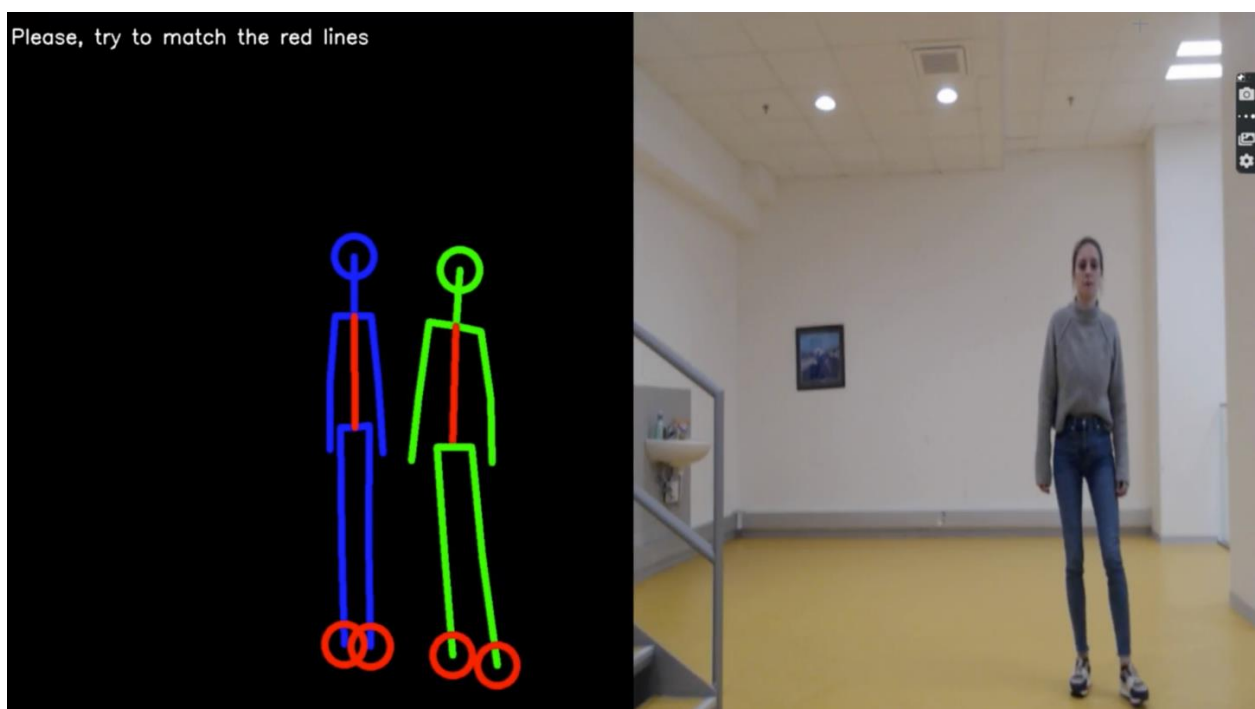
Figure 12: Matching the red lines for equalization of height
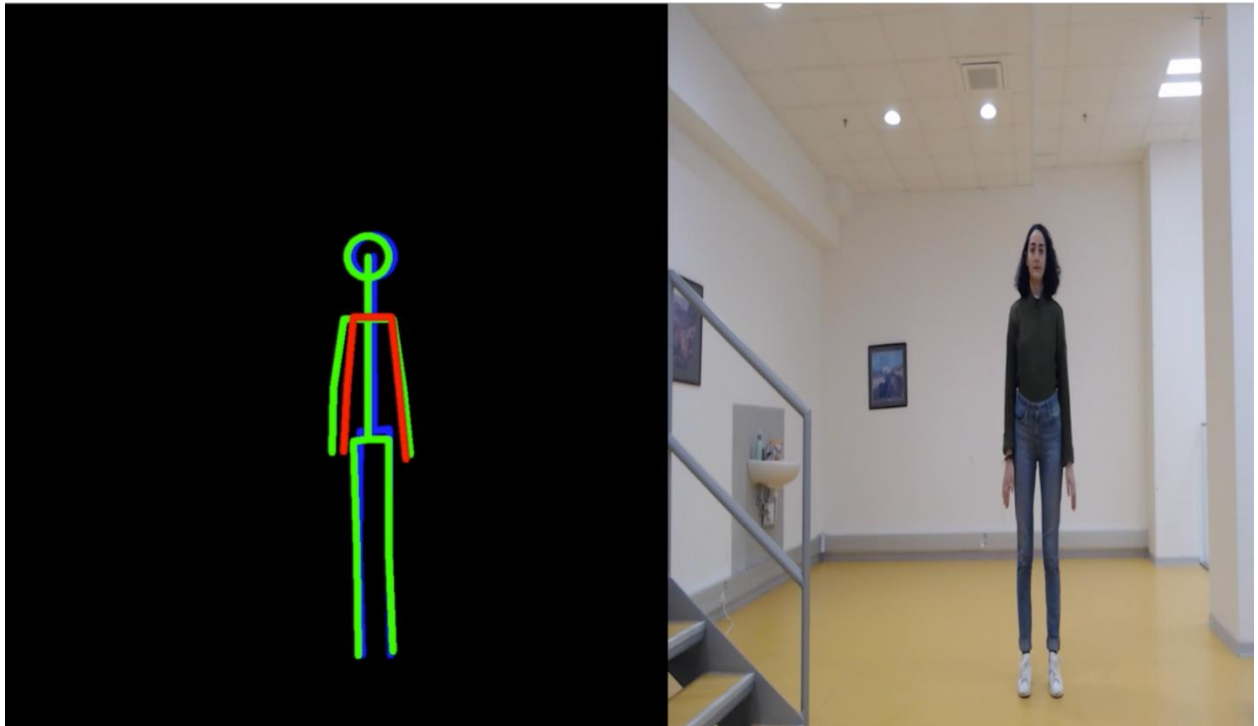
Figure 13: Adjusting the position of the user so that both skeletons overlap on the screen

Figure 14: The skeleton-matching feedback mode / the user exercises synchronically with the

blue skeleton

Figure 15: The mirror feedback mode / the option of the exercising with just the reference video of the trainer

Figure 16: The mixed feedback mode / exercising with the reference skeleton of the trainer

The feedback will be provided by the OpenPose pose detection system and a real-time application. There are mainly three conditions for the feedback modes: skeleton-matching, mixed, and mirror.

In the skeleton-matching feedback mode, the differences between the user's motion and the trainer's motion are provided. The feedback looks like two skeletons. The first skeleton is drawn from the trainer's motion that is prerecorded and the second skeleton is drawn from the user's motion which is updated in real-time. The two skeletons overlap on the screen. Thus, users can control the position and rhythm.

In the mixed feedback mode, the differences between the user's motion and the trainer's motion are also provided. It is similar to the skeleton-matching mode, but the program shows the user's video in real-time instead of using skeleton for the user's motion. Thus, the user sees her/his own body on the screen with the reference skeleton of the trainer. And for the mirror feedback mode, the program shows only the user's video in real-time and the user performs the exercise with only the trainer's prerecorded video.

For all types of feedback conditions, the screen is divided into two parts; one part is for the feedback modes and the other part always shows the trainer's prerecorded video.

4.7 Study design and final evaluation

The experiment involved exercising in front of the computer with the real-time feedback application. The study was prepared with 18 participants on the three different physiotherapy exercises. All participants performed three physiotherapy exercises respectively (Ex1:HASL, Ex2:SA, Ex3:SLS) under the three conditions (the skeleton-matching feedback mode, the mixed feedback mode, the mirror feedback mode). The order of the feedback modes for each participant was randomized.

Without feedback : the mirror mode
With feedback : the skeleton-matching mode
And the mixed mode

Exercise 1: HASL

Exercise 2: SA

Exercise 3: SLS

The expected duration of the experiment within one participant was 30 minutes. Exclusion criteria were having an acute illness (infectious, traumatic, inflammatory), decompensated chronic illness (internal, neurological) or oncological illness, or being in convalescence after illness or injury. Participation in the experiment was completely voluntary, without the right to any reward.

Participants took the right position to start the exercise after running the real-time feedback application. Then the screen was separated into two parts. One part always showed the trainer's prerecorded video and the other part showed the feedback modes for each condition. The feedback helped the participant to exercise synchronically with the trainer's video. For the without feedback part of the study, the same procedure was performed but the application presented only real-time video of the participant instead of types of feedback. After each condition, participants were asked to respond anonymously the questionnaire concerning their most recent experience of exercise.

Hypotheses:

H1: Exercising with our system is performed better (more correctly) than with videos only

H2: Our system induces higher motivation to perform exercising at the moment (and also regularly) than videos only

H3: Our proposed feedback for exercise is more effective than with videos in terms of understanding/clarity

- Helpfulness of feedback
- Subjective performance
- duration of adjustment until correct pose is attained
- duration of correctly maintaining the pose

H4: Our feedback for exercising is more preferred by the users

Metrics:

Evaluation of the first hypothesis was performed with the objective evaluation in Matlab. And the second, third and fourth hypotheses will be evaluated from the questionnaire.

4.7.1 Questionnaire Plan

The questionnaire consisted of five parts. The first part is for obtaining demographic data and general data. The second part, the third part and fourth part will be completed by the participants after performing the first set, second set and third set of exercises respectively. The fifth part is concluding questions for experiment.

4.7.1.1   Demographic and general information

Initial questionnaire - before study

1) What is your age range?
2) What is your gender?
3) What is your occupation? (e.g. student, engineer, teacher, project manager,...)
4) How many hours do you spend sitting PER DAY? (Try to think of the average, including time sitting on the train, in the car, on the couch,...)
5) How many hours a WEEK do you spend exercising? (Try to think of the average, including biking, walk to work, etc.)
6) How often do you do stretching exercises? (This may also be part of a longer workout.)

Participants have signed an informed consent and have been informed that they can withdraw from the study at any time, without giving a reason and without any financial, legal, or other consequences. Also, they all agreed that the course of their exercise will be recorded on camera and after the end of the study the data will be removed and no personal data or recordings will ever be published during the evaluation.

4.7.1.2   For each condition

1) The visual exercise instructions were clearly understandable.
2) It was hard to understand the correct pose that I should make from the visual instructions.
3) Throughout the exercise it was always clear to me how well I was doing.
4) The visual feedback allowed me to detect when I needed to adjust my pose to improve the exercise.

5) I perceived the visual instructions as helpful.

6) The visual feedback helped me to perform my exercise tasks.

7) The visual instructions did NOT help me to exercise correctly.

8) The exercise tasks were physically difficult for me.

9) I performed well in all exercise tasks.

10) The visual feedback motivated me to do the exercise pose correctly.

11) The visual feedback motivated me to maintain the exercise pose for longer than I might do otherwise.

12) Using such visual feedback could motivate me to do exercises more regularly in the future.

13) I would like to use such exercise feedback during my exercises in future.

14) How do you rate your performance with the single-leg squat exercise?

15) Please explain your rating, why do you think your performance was good/bad with the single-leg squat exercise.

16) How do you rate your performance with the hip abduction standing exercise?

17) Please explain your rating, why do you think your performance was good/bad with the hip abduction standing exercise.

18) How do you rate your performance with the symmetry abduction exercise?

19) Please explain your rating, why do you think your performance was good/bad with the symmetry abduction exercise.

4.7.1.3   Final conclusion

The last part of the questionnaire is for after participants have tried the three conditions. It includes the most important questions.

1) Which type of visual exercise feedback did you prefer?

2) Why did you prefer the selected type of exercise feedback?

3) What would you imagine having as different visual exercise feedback in the app except for three conditions which you already exercise?

4.7.2 Ethics Committee Approval

The project Use of camera-based pose estimation in telerehabilitation is a diploma thesis project of the Faculty of Biomedical Engineering and the Czech Institute of Informatics, Robotics, and Cybernetics of the Czech Technical University in Prague.

This experimental study took place at the Czech Institute of Informatics, Robotics, and Cybernetics of the Czech Technical University in Prague. Ethical approval for this study (C22/2022) were obtained from Faculty of Biomedical Engineering, Czech Technical University in Prague.

4.7.3 Subjects

All participants have signed an informed consent and have been informed that they can terminate the experiment at any time without giving any reason. Also, they all agreed that the course of their exercise will be recorded on camera and records will be kept confidential and will not, to the extent guaranteed by law, be made public.

Eligible 18 subjects participating in the study were selected from students who did not have any significant health problems.

General information of subjects were evaluated by initial questionnaire.

1) All subjects were in group 18-25 age range.
2) Gender of the subjects ; 4 females,14 males.
3) Occupation of the subjects ; 100% student.
4) How many hours do you spend sitting PER DAY? (Try to think of the average, including time sitting on the train, in the car, on the couch,...) ; 6 persons in 2 to 6 hours, 11 persons in 6 to 10 hours, 1 person in 10-16 hours.

5) How many hours a WEEK do you spend exercising? (Try to think of the average, including biking, walk to work,etc.) ; 12 persons in 2 to 6 hours, 2 persons in 6-10 hours, 4 persons in less than 2 hours.

6) How often do you do stretching exercises? (This may also be part of a longer workout.)
; 1 person in Multiple times per day, 2 persons in Multiple times per week, 2 persons in At least once weekly, 2 persons in At least once a month, 4 persons in Less than once a month, 7 persons in Never.

4.7.4 Objective evaluation of the study

The final evaluation was provided with analysis of body movement between the recorded videos of trainer and users. Openpose system processed each frame from the trainer's video to localize human body joints, also known as body key points. During the study the real time application saved all body key points for each subject's recording. The x, y coordinates of each body key points were stored into mat files for each frame from the user camera and from the trainer video.

Each subject performed exercises 1 (HASL), 2 (SA) and 3 (SLS), respectively, in a random feedback sequence for the skeleton matching mode, the mixed mode, the mirror mode (without feedback). Thus, after user study, 9 Matlab files were obtained for each participant. In order to evaluate whether the exercises was successfully performed under the feedback modes by the participants, the similarity of the exercise performance of the participants with the exercise performance of the trainer was compared. For each video frame, the distance between the x, y coordinates of the body key points from the trainer exercise video and the x, y coordinates of the participants were compared. This evaluation was executed in Matlab.

All body key points of the trainer and subjects were extracted from these mat files.The distance between the x, y coordinates was calculated with a simple formula. Considering that the subjects adapted to exercise towards the last seconds, the distance comparison between the body key points was calculated by including only the last frames. This calculation was performed by writing a small program for 3 exercise videos of each participant in 3 feedback modes. The final distances were obtained as mean values of euclidean distance from calculation among 25 body key points, and the results of all participants for feedback the mirror mode (without feedback), the skeleton matching mode and the mixed mode on the 3 exercises are shown in tables (Table1, 2 and 3). For example, if the distance between the three exercises is

less than the other two exercises, it can be concluded that that exercise is performed by the subject closer to the exercise performance of the trainer, in other words, the lower the distance the better.

4.7.5 Statistical Evaluation

The paired-sample t-test compares the means of two measurements taken from related units. A p-value less than 0.05 ($p \leq 0.05$) is statistically significant. It indicates strong evidence against the null hypothesis. The statistical evaluation was done using a custom written MatLab program (MatLab R2021b, Mathworks, Inc., Natick, MA, USA). Each subject practiced the exercises with feedback (the skeleton matching mode, the mixed mode) and without feedback (the mirror mode). In order to be able to clearly say in which type the participant performed the exercise better (i.e. more similar to the trainer), the paired-sample t-test was performed between exercises performed without feedback and with feedback.

5 Results

In this section, the results were divided into two parts. The results from questionnaire and the calculated distance values from the movement analysis.

5.1 Pose accuracy with distance measurements for each feedback mode

Table 1, 2 and 3 represent the distance differences between the trainer and subjects performance in three exercises. The values are presented in three separate tables for each feedback mode. Lower values were considered more valuable because they indicate that the difference between the subject and trainer is less.

Table 1: Distance differences for the mirror feedback mode

	Exercise1	Exercise2	Exercise3
Subject 1	45.312	37.483	75.676
Subject 2	48.175	27.197	56.589
Subject 3	73.473	51.731	72.383
Subject 4	74.570	41.469	53.562
Subject 5	40.709	56.302	65.060
Subject 6	37.039	42.523	52.931
Subject 7	63.853	44.577	53.395
Subject 8	34.736	38.443	42.211
Subject 9	96.973	31.078	57.724
Subject 10	44.329	78.437	73.607
Subject 11	88.873	33.220	34.258
Subject 12	44.821	24.027	29.955
Subject 13	83.879	51.035	56.842
Subject 14	29.980	26.103	28.072
Subject 15	35.046	35.973	40.617
Subject 16	74.063	62.576	59.236
Subject 17	36.343	28.278	44.998
Subject 18	74.209	47.525	60.710

Table 2: Distance differences for the skeleton-matching feedback mode

	Exercise1	Exercise2	Exercise3
Subject 1	40.280	37.569	28.503
Subject 2	26.364	28.550	26.180
Subject 3	48.702	53.359	69.760
Subject 4	83.967	39.247	65.332
Subject 5	51.330	54.982	43.359
Subject 6	66.160	40.435	50.357
Subject 7	68.159	38.203	43.618
Subject 8	43.661	31.933	31.851
Subject 9	87.202	33.806	62.478
Subject 10	36.291	29.626	44.361
Subject 11	68.738	22.039	34.499
Subject 12	55.987	40.551	38.287
Subject 13	67.116	38.379	71.610
Subject 14	27.964	48.464	39.869
Subject 15	65.756	29.576	50.153
Subject 16	57.800	54.540	59.351
Subject 17	48.617	32.983	50.901
Subject 18	43.421	43.272	56.732

Table 3: Distance differences for the mixed mode

	Exercise1	Exercise2	Exercise3
Subject 1	29.162	46.243	39.385
Subject 2	52.118	25.794	57.401
Subject 3	62.087	37.546	57.207
Subject 4	98.517	66.858	70.018
Subject 5	59.417	51.109	65.181
Subject 6	60.707	77.446	131.812
Subject 7	43.970	100.214	41.914
Subject 8	62.024	36.842	34.461
Subject 9	46.397	35.095	29.822
Subject 10	42.875	38.756	41.116
Subject 11	54.104	52.424	61.853
Subject 12	49.013	28.378	42.894
Subject 13	60.091	48.210	72.839
Subject 14	28.836	29.809	27.172
Subject 15	35.449	36.564	37.742
Subject 16	62.430	55.824	64.672
Subject 17	51.127	30.909	33.069
Subject 18	62.882	40.615	45.562
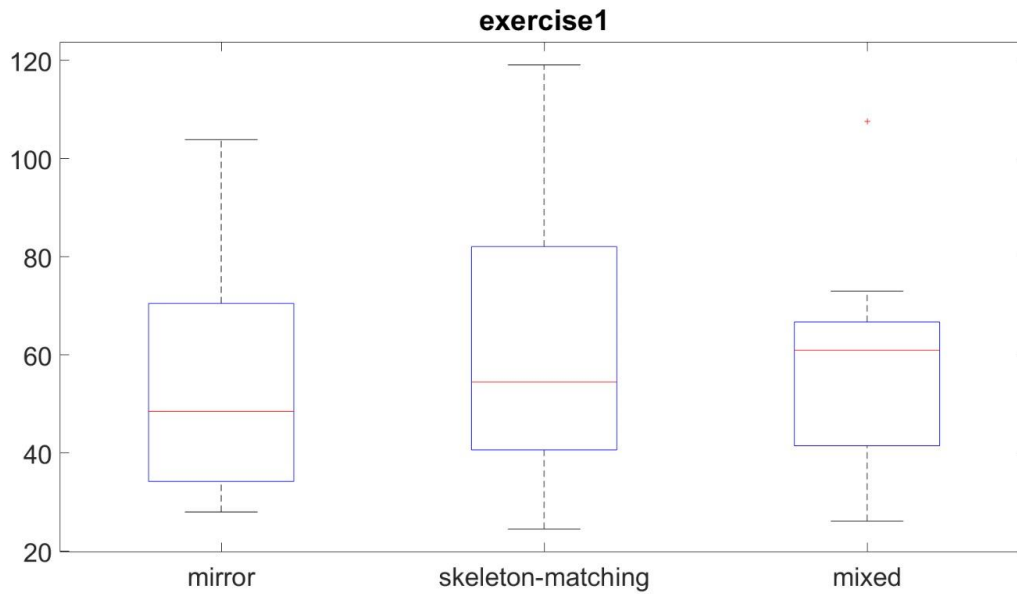
Figure 17:Comparison of distance differences for the feedback modes in exercise 1(HASL)

In exercise 1 (HASL), statistical significance was calculated between the skeleton matching feedback mode and the mirror feedback mode (no feedback), the mixed mode and the mirror mode, the mixed mode and the skeleton matching mode.

Statistical significance was not found between the feedback modes. Suprisingly, the skeleton matching mode was worse than the mirror mode (no feedback), but not significant. And the mixed mode was on almost the same as the mirror mode.
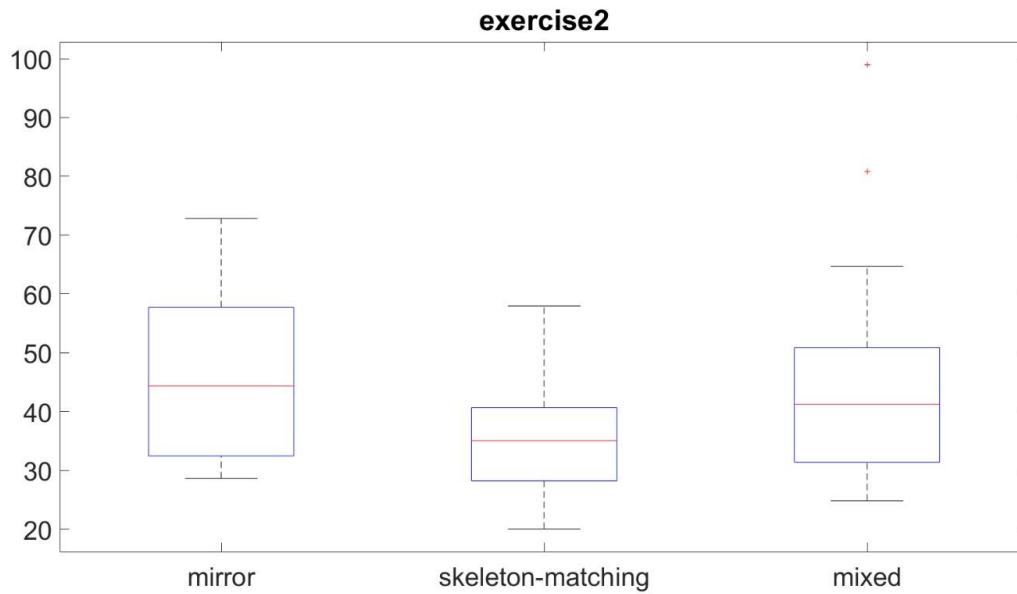
Figure 18:Comparison of distance differences for the feedback modes in exercise 2 (SA)

In exercise 2 (SA), statistical significance was calculated between the skeleton matching feedback mode and the mirror feedback mode (no feedback), and mirror mode, mixed mode and the skeleton matching mode.

Hovewer no statistical significance was demonstrated between any of combination of the feedback modes. The values were very similar to each other.
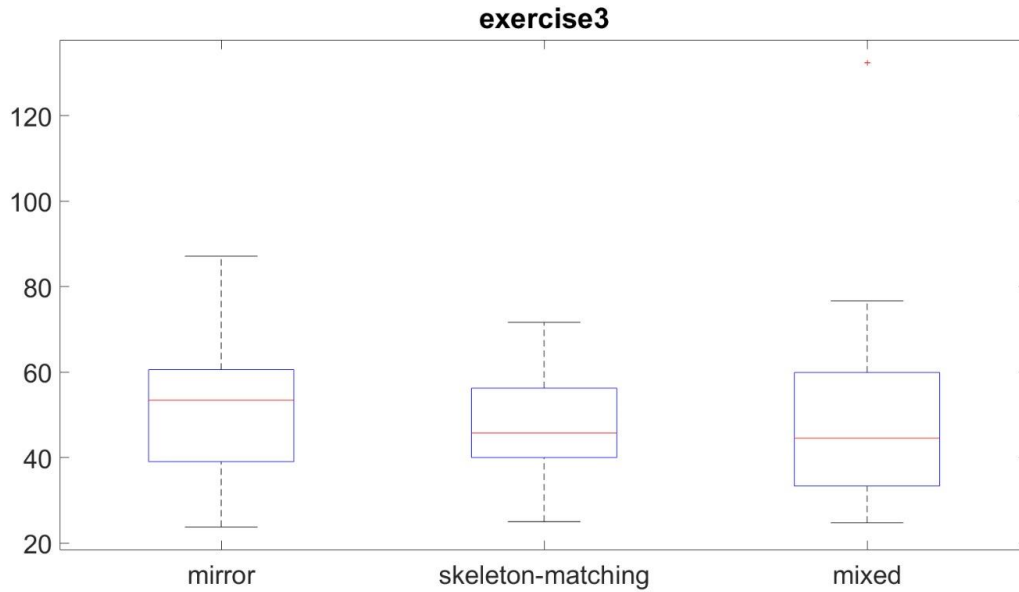
Figure 19: Comparison of distance differences for the feedback modes in exercise 3 (SLS)

In exercise 3 (SLS), statistical significance was calculated between the skeleton matching feedback mode and the mirror feedback mode (no feedback), the mixed mode and the mirror mode, the mixed mode and the skeleton matching mode.

Statistical significance was not found between the feedback modes. Hovever, the skeleton matching mode and the mixed mode were shown better than the mirror (no feedback) mode.

Table 4: Staistical analysis of the feedback modes in exercises 1, 2 and 3, p-values

	skeleton matching - mirror	mixed – mirror	mixed - skeleton matching
Ex 1	0.615	0.478	0.734
Ex 2	0.333	0.362	0.117
Ex 3	0.228	0.973	0.423

The table summarize the p-values of feedback couples in three separate exercise model. Statistical significance was not found between any of the feedback groups.

Table 5: Differences between the feedback modes in exercises 1, 2 and 3

	skeleton matching - mirror	mixed – mirror	mixed - skeleton matching
Ex 1	-2.159	-3.620	-1.461
Ex 2	-3.359	4.480	7.839
Ex 3	-5.034	-0.205	4.828

The above table demonstrates that the values of the mean distance differences between all subjects were calculated according to the respective exercise and the feedback mode.And the differences between the feedback modes were presented for the three exercises.

For instance, in exercise 1, the mean value of distance difference between the skeleton matching and the mirror mode is -2.159. This means the mean distance difference between trainer and subjects performances in the skeleton matching mode is less than the mirror mode.

5.2 Questionnaire

The most important part of the questionnaire was asking subjects' personal preferences about visual exercise feedback and asking them to evaluate.The preferences, 12 persons in the mixed mode, 6 persons in the skeleton-matching mode, see Figure 21.

Which type of visual exercise feedback did you prefer?
18 yanıt
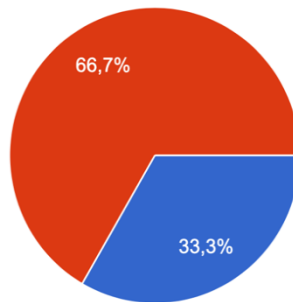
Figure 20: Subject's personel preferences for exercise feedback mode from the questionnaire
(the skeleton matching mode in blue, the mixed mode in red)

Table 6: Mean of the subjects' votes represented by the difference between pairs of feedback
for each question.

	skeleton matching- mirror	mixed - mirror	mixed - skeleton matching
Question 1	-0.222	-0.666	-0.444
Question 2	-1.611	-0.666	0.944
Question 3	0.166	0	-0.166
Question 4	-0.500	-0.666	-0.166
Question 5	-0.555	-0.555	0
Question 6	-0.222	-0.277	-0.055
Question 7	0.388	0.500	0.111
Question 8	-0.166	0.222	0.388
Question 9	0.166	-0.333	-0.500
Question 10	-0.277	-0.611	-0.333
Question 11	-0.611	-1.388	-0.777
Question 12	-0.166	-0.500	-0.333
Question 13	-0.055	-0.333	-0.277
Question 14	0.666	0.333	-0.333
Question 16	0.333	0.055	-0.277
Question 18	0.166	-0.111	-0.277

The questionnaire included the questions to investigate whether the feedback modes are beneficial for subjects about understanding of the feedback modes, helpfulness of guidance, subjective performance, motivation, preference. The questiones were voted by subjects during the experiment between 7 (strongly agree) and 1 (strongly disagree). All questiones were demostrated in the qustionnaire plan - condition section of the thesis.

The mean values of votes for the questions answered by participants for the feedback modes, representation by difference between the feedback pairs in the above table. It was represented by the difference between pairs of feedback for each question (Table 6).

The questions 1, 2 and 3 in the questionnaire evaluated whether participants found understandable for the exercises they did with and without feedback. Compared to the mean difference calculated between the skeleton matching mode and the mirror mode (without feedback), the skeleton matching feedback mode was found to be more understandable. In the difference between the mixed mode and the mirror mode, the mixed was generally more understandable. And in the difference between the mixed and the skeleton matching mode, the skeleton matching mode was more understandable.

The question 4, 5, 6 and 7 were asked to measure whether the guidance of the visual feedback is helpful for the subjects. The mixed mode and the skeleton matching mode were found to be almost equally helpful. Surprisingly, in the difference between the skeleton matching mode and the mirror mode, the skeleton matching mode was less helpful than the mirror mode (without feedback). And similarly, in the mean difference between the mixed mode and the mirror mode, the mixed mode was less helpful than the mirror mode.

The questions 8, 9, 14, 16 and 18 were asked to assess how subjects found their subjective performance during the study. In the difference between the skeleton matching mode and the mirror mode (without feedback), the subjects thought that their performance in the exercises with the skeleton matching mode was better than their performance in the mirror mode (without feedback). In the difference between the mixed mode and the mirror mode, the subjects thought that their performance in the exercises with the mixed mode was worse than their performance in the mirror mode in questions 8, 9, and 18. And, between the mixed mode and the skeleton

matching mode, the exercises performed with the skleton matching mode were thought to be better than the exercises performed with the mixed mode.

Finally, the questions 10, 11, 12 were about their motivation with the feedback modes in the exercises. In exercises, subjects found the skeleton matching mode less motivating than the mirror mode (without feedback) and the mixed mode less motivating than the mirror mode. The difference between the mixed mode and the skeleton matching mode was that subjects found the skleton matching mode more motivating than the mixed mode.

6 Discussion

This chapter is divided into two separate sections as in the result chapter.

6.1 Interpretation of the distance measurements

This study was performed to find out whether visual feedback helps to people to execute their physical exercise. Three separate feedback modes, two with feedback and one without feedback, were used in the study.

However, no statistical significance was found in the results found by comparing the distance between the subject and the trainer's performance. This result revealed that the correct execution of physical movement cannot be found directly by distance calculation. In order to decide the exercise performance quality, not only the distance calculation, but also the comparison with other metrics is required.

Especially in the figure 17 for the exercise 1 (HASL), it was surprising that the skeleton matching mode and the mixed mode had a worse mean value than the mirror mode (without feedback), but this was only found for the exercise 1 (HASL).

However, although statistical significance for the feedback modes was not found in any of the selected exercises, there were slight improvements with the with the feedback modes in the results. The performances of the subjects for exercises 2 (SA) and 3 (SLS) were slightly better than the performance the mirror mode (Figure 18, 19). This highlights that results may vary depending on the type of exercise.

The findings from the distance measurement showed that the results are worse with the feedback modes. Comparison of distance differences does not mean, that the exercise was performed properly. Therefore, future steps will be to rate the exercises by physiotherapist.

6.2 Interpretation of the questionnary

Despite the results from the movement analysis, the responses from the questionnaire showed that subjects liked the exercises with feedback (the skeleton matching mode and the mixed mode) more than mirror mode (without feedback), see Figure 21.

The observation from the results obtained from the other questions in the questionnaire:
The subjects may have thought that their performance was good because they did not see their mistakes while performing the exercises in the mirror mode (without feedback). Therefore, the mean vote rate of the exercises with the skeleton matching mode and the mixed mode in the voting in the questionnaire may have been lower.
Those 3 exercises performed by the participants with the feedback modes were different from daily exercises since they were physiotherapy exercises. Exercises 1 (HASL) and 3 (SLS) are relatively difficult compared to exercise 2 (SA). Thus, the feedback that informs them that they are not performing the exercise well can be frustrating.

Performing exercises with feedback may take some time to get used to, but it would be helpful and motivating to continue physical practice at home alone after learning the main points of the exercises from the trainer in the first session.

7 Conclusions and future work

It is clear that only the measurement of distance is insufficient to find out the positive effect of feedback on exercise performance. On the other hand, I think that this system is worth more research and trying new methods, considering that this system is inexpensive and accessible to everyone compared to other motion analysis systems.

For future use of the system, it may consider working with experts in this field and make additions on the measurement method. By changing the method of the exercise, the real-time feedback application can begin with the introduction of the exercises. This allows users to practice in front of the screen for a few minutes with exercises, then versions of the exercises with and without feedback modes can be tested for quality of exercise. Thus, the exercise would be experienced by the participant before the performance evaluation. This eliminates the difference of exercise information that varies from person to person, and the user can simply focus on adapting to the feedback modes.

The qualitative assessment by the physiotherapist will be the next step of the this project. Professional physiotherapists will watch at the records of all the exercises performed and rated whether participants performed the exercise better with or without feedback.

List of Literature

[1] C. E. Garber, B. Blissmer, M. R. Deschenes, B. A. Franklin, M. J. Lamonte, I. M. Lee, D. C. Nieman and D. P. Swain, "Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise," *Medicine and science in sports and exercise,* vol. 43, no. 7, pp. 1334-1359, 2011.

[2] J. E. Bielecki and P. Tadi, Therapeutic Exercise, Treasure Island (FL): StatPearls Publishing, 2022.

[3] C. Schonauer, T. Pintaric, H. Kaufmann, S. Jansen-Kosterink and M. Vollenbroek-Hutten, "Chronic pain rehabilitation with a serious game using multimodal input," in *International Conference on Virtual Rehabilitation*, Zurich, 2011.

[4] W. Ren, F. Pu, X. Fan, S. Li, L. Sun, D. Li, Y. Wang and Y. Fan, "KINECT-BASED SKELETON-MATCHING FEEDBACK FOR MOTOR REHABILITATION: TRANSIENT PERFORMANCE EFFECT OF SHOULDER TRAINING," *Journal of Mechanics in Medicine and Biology,* vol. 16, no. 3, 2016.

[5] M. M. Gharasuie, N. Jennings and S. Jain, "Performance Monitoring for Exercise Movements using Mobile Cameras," in *BodySys 2021 - Proceedings of the 2021 ACM Workshop on Body Centric Computing Systems*, Wisconsin, 2021.

[6] J. Chua, L. Y. Ong and M. C. Leow, "Telehealth using posenet-based system for in-home rehabilitation," *Future Internet,* vol. 13, no. 7, 2021.

[7] J. Chua, L. Y. Ong and M. C. Leow, "Telehealth Using PoseNet-Based System for In-Home Rehabilitation," *Future Internet,* vol. 13, no. 7, 2021.

[8] T. Hellsten, J. Karlsson, M. Shamsuzzaman and G. Pulkkis, "The Potential of Computer Vision-Based Marker-Less Human Motion Analysis for Rehabilitation," *Rehabilitation Process and Outcome,* vol. 10, 2021.

[9] S. Gaoyue, "Golf Swing Correction Based on Deep Learning Body Posture Recognition; Golf Swing Correction Based on Deep Learning Body Posture Recognition," New York, 2021.

[10] R. Baker, A. Esquenazi, M. G. Benedetti and K. Desloovere, "Gait analysis: clinical facts," *European journal of physical and rehabilitation medicine,* vol. 52, no. 4, 2016.

[11] "Introduction to Movement Analysis - CMAS," [Online]. Available: https://cmasuki.org/introduction-to-movement-analysis/. [Accessed 29 03 2022].

[12] M. H. Khan, M. Zöller, M. S. Farid and M. Grzegorzek, "Marker-based movement analysis of human body parts in therapeutic procedure," *Sensors (Switzerland),* vol. 20, no. 11, pp. 1-19, 2020.

[13] W. Y. Wong, M. S. Wong and K. H. Lo, "Clinical applications of sensors for human posture and movement analysis: A review," *Prosthetics and Orthotics International,* vol. 31, no. 1, pp. 62-75, 2007.

[14] A. Godfrey, R. Conway, D. Meagher and G. ÓLaighin, "Direct measurement of human movement by accelerometry," *Medical Engineering and Physics,* vol. 30, no. 10, pp. 1364-1386, 2008.

[15] Q. Wang, W. Chen, A. A. Timmermans, C. Karachristos, J. B. Martens and P. Markopoulos, "Smart Rehabilitation Garment for posture monitoring," in *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Milan, 2015.

[16] G. Bleser, D. Steffen, M. Weber, G. Hendeby, D. Stricker, L. Fradet, F. Marin, N. Ville and F. Carré, "A personalized exercise trainer for the elderly," *Journal of Ambient Intelligence and Smart Environments,* vol. 5, no. 6, pp. 547-562, 2013.

[17] N. K. Mangal and A. K. Tiwari, "A review of the evolution of scientific literature on technology-assisted approaches using RGB-D sensors for musculoskeletal health monitoring," *Computers in Biology and Medicine,* vol. 132, 2021.

[18] S. A. Skogstad, A. R. Jensenius, S. St°, S. A. Skogstad, A. R. Jensenius and K. Nymoen, "Using IR Optical Marker Based Motion Capture for Exploring Musical Interaction Timing and Sound in Musical Microrhythm (TIME) View project Musical Gestures View project Using IR Optical Marker Based Motion Capture for Exploring Musical Interaction," NIME2010, Sydney, 2010.

[19] "Vicon | Award Winning Motion Capture Systems," 2022. [Online]. Available: https://www.vicon.com/. [Accessed 4 1 2022].

[20] F. Mun, S. W. Suh, H. J. Park and A. Choi, "Kinematic relationship between rotation of lumbar spine and hip joints during golf swing in professional golfers," *BioMedical Engineering Online,* vol. 14, no. 1, 2015.

[21] P. Merriaux, Y. Dupuis, R. Boutteau, P. Vasseur and X. Savatier, "A Study of Vicon System Positioning Performance," *Sensors,* vol. 17, no. 7, 2017.

[22] C. D. Novo, S. Profile, S. Alharbi, E. Biden and V. L. Chester, "Spatial characterization of the accuracies in "Vicon" Motion Analysis Laboratory. Assessment of the assistive devices industry in Canada View project Adapting Isokinetic Dynamometry for people with lower-limb amputations View project," 2011.

[23] Y. H. Yang, W. Xu, H. Zhang, J. P. Zhang and M. L. Xu, "The application of KINECT motion sensing technology in game-oriented study," *International Journal of Emerging Technologies in Learning,* vol. 9, no. 2, pp. 59-63, 2014.

[24] R. Lun ve W. Zhao, «A Survey of Applications and Human Motion Recognition with Microsoft Kinect,» *International Journal of Pattern Recognition and Artificial Intelligence,* cilt 29, no. 5, 2015.

[25] B. Lange, C.-Y. Chang, E. Suma, B. Newman, A. S. Rizzo and M. Bolas, "Development and evaluation of low cost game-based balance rehabilitation tool using the Microsoft Kinect sensor," *Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference,* 2011.

[26] M.-C. Huang, W. Xu, Y. Su, B. Lange, C.-Y. Chang and M. Sarrafzadeh, "SmartGlove for Upper Extremities Rehabilitative Gaming Assessment," 2012.

[27] M. A. Rahman, A. M. Qamar, M. A. Ahmed, M. Ataur and R. Saleh Basalamah, Multimedia Interactive Therapy Environment for Children Having Physical Disabilities, ICMR, 2013.

[28] X. Huang, D. Pan, Y. Huang, J. Deng, P. Zhu, P. Shi, R. Xu, Z. Qi and J. He, "Intelligent Yoga Coaching System Based on Posture Recognition," *2021 International Conference on Culture-oriented Science Technology (ICCST),* pp. 290-293, 2021.

[29] "GitHub - CMU-Perceptual-Computing-Lab/openpose: OpenPose: Real-time multi-person keypoint detection library for body, face, hands, and foot estimation," 2022. [Online]. Available: https://github.com/CMU-Perceptual-Computing-Lab/openpose. [Accessed 4 May 2022].

[30] J. Adolf, J. Dolezal, P. Kutilek, J. Hejda and L. Lhotska, "Single Camera-Based Remote Physical Therapy: Verification on a Large Video Dataset," *Applied Sciences ,* vol. 12, no. 2, p. 799, 2022.

[31] Ł. Kidziński, B. Yang, J. L. Hicks, A. Rajagopal, S. L. Delp and M. H. Schwartz, "Deep neural networks enable quantitative movement analysis using single-camera videos," *Nature Communications,* vol. 11, no. 1, pp. 1-10, 2020.

[32] L. Huang and G. Liu, "Functional motion detection based on artificial intelligence," *Journal of Supercomputing,* vol. 78, no. 3, pp. 4290-4329, 2022.

[33] Z. Cao, T. Simon, S.-E. Wei and Y. Sheikh, "Realtime Multi-Person 2D Pose Estimation using Part Affinity Fields," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 43, no. 1, pp. 172-186, 2021.

[34] M. Ota, H. Tateuchi, T. Hashiguchi, T. Kato, Y. Ogino, M. Yamagata and N. Ichihashi, "Verification of reliability and validity of motion analysis systems during bilateral squat using human pose tracking algorithm," *Gait & Posture,* vol. 80, pp. 62-67, 2020.

[35] K. Otsuka, N. Yagi, Y. Yamanaka, Y. Hata and Y. Sakai, "oint Position Registration between OpenPose and Motion Analysis for Rehabilitation," *Proceedings of The International Symposium on Multiple-Valued Logic,* pp. 100-104, 2020.

[36] "Physiotools," [Online]. Available: https://www.physiotools.com/. [Accessed 4 May 2022].

List of Appendices

1.Appendix: Decleration attachment

This project was carried out in collaboration with other team members.

Jindřich Adolf, Ph.D. student in the department of Cognitive Systems and Neurosciences in the CIIRC. He was working on the project and had already created a very basic version of the application. Philomene Mazand, a student in the CTU, doing her internship in the CIIRC. Her mission was to improve the real-time feedback application.

Jaromir Dolezal, Ph.D. in the department of Cognitive Systems and Neurosciences and Analysis of human motion in the CIIRC. He continued to develop the application after Philomene's internship period. Philomene and I did our independent works under his supervision.

The selection and reproduction of the exercises in front of OpenPose to have an idea if the exercise could work with the application or not and the recording of the exercise videos were done by me and Philomene.

My main part was to create the study to verify the efficiency of the visual feedback with the real-time feedback application.

I performed the evaluation of the exercises to decide the usability by the feedback application and OpenPose system. For this point, I created a small program to extract information about the key points in the video of the exercises like the percentage of missing points, and the mean confidence. And I selected critical points from the each exercise video. It indicates some angles and relative distances between the body key points. Evaluation the performance with the critical poins is needed for the following of the project. But also they are used in the feedback application as an important feature.

I made some exercise videos with feedback using the real-time application for testing. And I had a consultation with the professional physiotherapist to discuss which exercises are the most suitable for the purpose. Then I designed the study in which participants will exercise in front of a camera and get visual feedback on the computer screen to demonstrate the effect of visual feedback on exercise performance. And I found some questions for the questionnaire which evaluate some of our hypotheses. And I reached the final result by evaluating the distance metric. After my thesis, the experiment will still continue with a more number of participants to achieve the maximum extent of results.

2.Appendix: Ethics Board Review

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE
Fakulta biomedicínského inženýrství
nám. Sítná 3105, 272 01 Kladno

Žádost o projednání výzkumného projektu v etické komisi FBMI ČVUT
Application for approval of a research project by FBMI CTU Institutional Ethical/Review Board

Název projektu: Využití odhadu postury v obraze pro telerehabilitaci
Name of the project: Use of camera-based pose estimation in telerehabilitation

Hlavní řešitel projektu (Jméno, pracoviště, e-mail):
BSc.Esra Diren, Fakulta biomedicínského inženýrství ČVUT v Praze, Katedra biomedicínské techniky
E-mail: direnesr@fbmi.cvut.cz

Stručný popis projektu (do 100 slov):

The project aims to demonstrate the effect of visual feedback on exercise performance. An experiment will be designed in which participants will exercise in front of a camera, while real-time visual feedback will be presented on a computer screen. The exercise performance will be compared between the "feedback" and "without feedback" arms of the study.

Charakter projektu: ~~Grantová úloha (název agentury):~~
~~Výzkum výzkumného týmu (specifikace):~~
~~Kvalifikační práce (specifikace):~~
Jiné: Diploma Thesis

Seznam přikládaných dokumentů:
- sylabus projektu
- informovaný souhlas vč. informace pro subjekt hodnocení
- strukturovaný životopis hlavního řešitele, je-li na FBMI externistou
- jiné (prosíme vypsat):

V Kladně dne 22.04.2022

_____
podpis hlavního řešitele

Vyjádření souhlasu etické komise FBMI ČVUT
FBMI CTU Institutional Ethical/Review Board approval

Projekt byl schválen etickou komisí FBMI ČVUT dne: 12.4.2022   **platný do:** 31.5.2022
pod číslem: C22/2022

Etická komise FBMI ČVUT v Praze, ve složení Mgr. Martina Dingová Šliková (předsedkyně), prof. Ing. Karel Roubík, Ph.D., RNDr. Táňa Jarošíková, CSc., Ing. Petr Kudrna, PhD., MUDr. Radek Matlach, a Ing. Lucie Šedzmáková, zhodnotila předložený projekt a neshledala žádné rozpory s platnými zásadami, předpisy a mezinárodními směrnicemi pro provádění biomedicínského výzkumu zahrnujícího lidské účastníky nebo laboratorní zvířata.

Řešitel projektu splnil podmínky nutné k získání souhlasu etické komise.

ETICKÁ KOMISE
České vysoké učení technické v Praze
Fakulta biomedicínského inženýrství
nám. Sítná 3105
272 01 Kladno

V Kladně dne 12.4.2022

_____
razítko etické komise FBMI ČVUT

Mgr. Martina Dingová Šliková, Ph.D.

_____
podpis předsedy etické komise

3.Appendix: Determining the usability of the pose estimation for the exercises

Table 7: Determining the usability of the pose estimation for the exercises. All exercises are from the front and are suitable for the OpenPose system. All exercises are slow for the visual feedback modes. A-Angle, RD- Relative distance.

Exercise	Pct. of missing points	Mean confidence	Critical points for feedback	Important features
ACO	3.100	0.778	A(3-2-1) ,A(6-5-1)	1-2,2-3,5-6,1-5
ANLFSL	0	0.802	RD(12-7),A(0-1-2)	0-1,1-2,6-7,8-12
ANLFSR	0	0.802	RD(4-9),A(0-1-5)	0-1,1-5,3-4,8-9
ARHFR	4.497	0.795	A(9-10-11)	9-10,10-11
ACML	5.310	0.646	A(8-1-5)	1-8,1-5
ACMR	6.312	0.657	A(8-1-2)	1-2,1-8
BOLR	0.295	0.629	A(4-2-1),A(1-5-7)	1-2,2-3,3-4,1-5,5-6,6-7
CH	7.337	0.743	A(12-13-14)	12-13,13-14,9-10,10-11
CS	1.542	0.762	RD(11-14)	12-13,13-14,9-10,10-11
HAL	5.088	0.584	RD(10-13)	8-12,12-13,13-14,8-9,9-11
HALL	2.342	0.647	RD(11-14)	8-12,12-13,13-14,8-9,9-11
HALR	3.817	0.678	RD(11-14)	8-12,12-13,13-14,8-9,9-11
HAR	5.909	0.597	RD(11-14) ; A(8-9-11)	8-12,12-13,13-14,8-9,9-11
HASL	0	0.765	RD(11-14)	8-12,12-13,13-14,8-9,9-11

HASR	0	0.766	RD(14-11)	8-12,12-13,13-14,8-9,9-11
HERAL	0	0.806	A(12-13-14),RD(13-8)	8-12,12-13,13-14,8-9,9-11
HERAR	0	0.801	A(9-10-11),RD(8-10)	8-12,12-13,13-14,8-9,9-11
KFSL	0	0.755	A(12-13-14)	12-13,13-14
KFSR	0	0.780	A(9-10-11)	9-10,10-11
LLL	0.492	0.786	A(3-2-4),RD(11-14)	2-3,3-4,8-12,12-13,13-14,8-9,9-10,10-11
LLR	0	0.798	A(5-6-7),RD(14-11)	5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
LDU	0	0.778	RD(0-1)	0,0-1
LDU	0	0.784	RD(0-1)	0,0-1
MS	0	0.820	A(9-10-11)	8-12,12-13,13-14,8-9,9-11
OSNSL	8.495	0.628	A(5-6-7),A(0-1-2)	0-1,1-2,2-3,3-4,5-6,6-7
OSNSR	8.682	0.621	A(3-2-4),A(0-1-5)	0-1,2-3,3-4,5-6,6-7,1-5
POL	5.178	0.772	A(8-1-5), RD(11-14)	1-2,2-3,3-4,1-5,5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
POR	1.177	0.784	A(8-1-2),RD(11-14)	1-2,2-3,3-4,1-5,5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SEFE	14.954	0.673	A(5-6-7)	5-6,6-7
STLSCL	0	0.828	A(2-3-4)	0-1,1-8,1-2,2-3,3-4
STLSCR	0	0.832	A(5-6-7)	0-1,1-8,1-5,5-6,6-7
STLSFL	0	0.762	A(2-3-4)	0-1,1-8,1-2,2-3,3-4
STLSFR	0	0.752	A(5-6-7)	0-1,1-8,1-5,5-6,6-7
SORS	0	0.778	A(2-3-4),A(5-6-7)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SSE	0	0.722	A(2-3-4),A(5-6-7)	2-3,3-4,5-6,6-7

STES	11.379	0.699	A(3-2-1),A(6-5-1)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SAL	0	0.799	A(1-5-6)	1-5,5-6,6-7
SAR	0	0.806	A(1-2-3)	1-2,3-4,4-5
SAHL	0	0.782	RD(12-7)	1-5,5-6,6-7
SAHR	0	0.771	RD(4-9)	1-2,3-4,4-5
SFL	21.887	0.691	A(1-5-6)	1-5,5-6,6-7
SFR	10.415	0.623	A(1-2-3)	1-2,3-4,4-5
SP	23.925	0.728	A(4-3-2),A(5-6-7)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SR	19.954	0.731	A(1-2-3),A(1-5-6)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SSBAL	20	0.739	A(1-5-6)	1-5,5-6,6-7
SSBAR	19.711	0.737	A(1-2-3)	1-2,3-4,4-5
SWA	0	0.718	A(1-2-3),A(1-5-6)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SBSL	0.116	0.808	A(8-1-7)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SBSR	0	0.807	A(8-1-4)	0-1,1-8,1-2,2-3,3-4,1-5,5-6,6-7
SP	0	0.727	A(8-1-5)	0-1,1-2,2-3,3-4,5-6,6-7,1-5,1-8,8-9,8-12,9-10,10-11,12-13,13-14
SP1K	4.333	0.702	A(2-1-6)	0-1,1-2,2-3,3-4,5-6,6-7,1-5,1-8,8-9,8-12,9-10,10-11,12-13,13-14
SP2K	0.837	0.702	A(2-1-8)	0-1,1-2,2-3,3-4,5-6,6-7,1-5,1-8,8-9,8-12,9-10,10-11,12-13,13-14
SLSSFL	0	0.792	RD(11-14)	2-3,3-4,8-12,12-13,13-14,8-9,9-10,10-11

SLSSFR	0	0.787	RD(11-14)	5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SLSSSL	0	0.776	A(9-10-11),RD(11-14)	2-3,3-4,8-12,12-13,13-14,8-9,9-10,10-11
SLSSSR	0.0352	0.783	A(12-13-14),RD(11-14)	5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SLSHAL	0	0.785	RD(11-14)	2-3,3-4,5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SLSHAR	0	0.789	RD(11-14)	2-3,3-4,5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SMBAL	0.606	0.809	A(9-10-11),A(12-13-14),A(1-2-3) ,A(1-5-6)	1-2,2-3,3-4,1-5,5-6,6-7,8-12,12-13,13-14,8-9,9-10,10-11
SHAL	0	0.772	A(9-10-11),RD(11-14)	8-12,12-13,13-14,8-9,9-11
SHAR	0.620	0.763	A(12-13-14),RD(11-14)	8-12,12-13,13-14,8-9,9-11
SSFM	0.006	0.806	A(3-2-1),A(1-5-6)	1-2,2-3,3-4,1-5,5-6,6-7
SSHA	0.008	0.782	RD(4-9),RD(12-7)	1-2,2-3,3-4,1-5,5-6,6-7
STLFSL	16.972	0.702	A(1-5-6)	0-1,1-8,1-2,2-3,3-4
STLFSR	19.469	0.721	A(1-2-3)	0-1,1-8,1-5,5-6,6-7
SS	0.010	0.816	A(9-10-11),A(12-13-14)	2-3,3-4,5-6,6-7,9-10,10-11,12-13,13-14
TPL	2.222	0.758	A(1-2-4),A(12-13-14)	1-2,2-3,3-4,1-5,5-6,6-7,9-10,10-11,12-13,13-14
TPR	2.626	0.740	A(1-5-7),A(9-10-11)	1-2,2-3,3-4,1-5,5-6,6-7,9-10,10-11,12-13,13-14
TSBL	0	0.829	A(1-8-12)	1-2,2-3,3-4,1-8,8-12
TSBR	0.082	0.824	A(1-8-9)	1-5,5-6,6-7,1-8,8-9
WSS	8.307	0.768	A(9-10-11),A(12-13-14)	1-8,8-9,9-10,10-11,8-12,12-13,13-14

4.Appendix: List of Exercises

ACO	Active Chest Opening
ANLFSL	Active Neck Lateral Flexion Stretch Left
ANLFSR	Active Neck Lateral Flexion Stretch Right
ARHFR	Active Resisted Hip Flexion Right
ACML	Anterior Chain Mobility Left
ACMR	Anterior Chain Mobility Right
BOLR	Bent Over Lateral Raise
CH	Chair
CS	ChairSquat
HAL	Hip Abduction Left
HALL	Hip Abduction Lying Left
HALR	Hip Abduction Lying Right
HAR	Hip Abduction Right
HASL	Hip Abduction in Standing Left
HASR	Hip Abduction in Standing Right
HERAL	Hip External Rotation Activation Left
HERAR	Hip External Rotation Activation Right
KFSL	KneeFlexioninSittingLeft
KFSR	KneeFlexioninSittingRight
LLL	Lateral Lunge Left
LLR	Lateral Lunge Right
LDU	Looking Downward Upward
LDU	Looking Downwards and Upwards
MS	Mini Squat
OSNSL	Opener Segmental and Neural Sitting Left
OSNSR	Opener Segmental and Neural Sitting Right
POL	Psoas Opening Left
POR	Psoas Opening Right

SEFE	Seated Elbow Flexion Extension
STLSCL	Seated Lateral Trunk Stretch Chair Left
STLSCR	Seated Lateral Trunk Stretch Chair Right
STLSFL	Seated Lateral Trunk Stretch Floor Left
STLSFR	Seated Lateral Trunk Stretch Floor Right
SORS	Seated Overhead Reach Stretch
SSE	Seated Shoulder
STES	Seated Thoracic Extention with Shoulder Flex
SAL	Shoulder AbductionLeft
SAR	Shoulder Abduction Right
SAHL	Shoulder Abduction to Horizontal Left
SAHR	Shoulder Abduction to Horizontal Right
SFL	Shoulder Flexion Left
SFR	Shoulder Flexion Right
SP	Shoulder Press
SR	Shoulder Rotation
SSBAL	Shoulder Scaption with Bent Arm Left
SSBAR	Shoulder Scaption with Bent Arm Right
SWA	Shoulder Warm Up
SBSL	Side Bending Stretch Left
SBSR	SideBendingStretchRight
SP	Side Planck
SP1K	Side Planckon 1 Knee
SP2K	Side Planckon 2 Knees
SLSSFL	Single Leg Squat Sliding Forward Left
SLSSFR	Single Leg Squat Sliding Forward Right
SLSSSL	Single Leg Squat Sliding Sideway Left
SLSSSR	Single Leg Squat Sliding Sideway Right
SLSHAL	Single Leg Suquat with Hip Abduction Left
SLSHAR	Single Leg Suquat with Hip Abduction Right

SMBAL	Squat with Mini Band Around Legs
SHAL	Standing Hip Abduction Left
SHAR	Standing Hip Abduction Right
SSFM	Standing Shoulder Flexion Mobility
SSHA	Standing Shoulder Horizontal Abduction
STLFSL	StandingTrunkLateralFlexionStretchLeft
STLFSR	Standing Trunk Lateral Flexion Stretch Right
SS	SumoSquat
TPL	Triangle Pose Left
TPR	Triangle Pose Rigth
TSBL	Trunk Side Bending Left
TSBR	Trunk Side Bending Right
WSS	Wide Stance Squat