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Computer Vision-based Marker-less Real Time Motion Analysis for Rehabilitation – An Inter-disciplinary Research Project

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Abstract

An aging population and the concentration of healthcare services to urban areas are threats against the possibility to provide easily and equally achieved rehabilitation services for citizens. Telerehabilitation is a potential way of improving availability as rehabilitation services can be delivered to clients through telecommunication networks and the Internet and thus, clients do not need to physically travel anywhere for receiving therapy. Computer Vision (CV) - based marker-less real time motion analysis is a promising technique for automatically examining and giving feedback on therapeutic exercises to clients without the need for advanced and expensive technical equipment or being in contact with healthcare professionals in person. However, this telerehabilitation technique still needs to be rigorously tested and its accuracy must be optimized before it can be widely adopted in rehabilitation. This paper provides an overview of an interdisciplinary research project at Arcada University of Applied Sciences where students, teachers, and researchers from information technology, big data analytics, and physiotherapy study programmes collaborate in designing, developing and testing new CV-based marker-less prototype applications for rehabilitation purposes. For such a project to be successful the entire development process must be carefully planned and the communication between project members from different disciplines is highly significant. As guideline and theoretical method for the development of the CV prototype in this project the Centre for eHealth Research Roadmap (CeHRes) was implemented and used. The purpose of this paper is to describe the development process of a CV-based marker-less prototype application analysing and measuring the knee angle of clients. Preliminary performance results of the prototype application are presented as well as experience and outcomes from this interdisciplinary project from an educational point of view.

Keywords: computer vision, interdisciplinary, prototype, OpenPose, DensPose

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1 INTRODUCTION

Providing easily and equally achieved rehabilitation services is a significant challenge due to the aging population and the concentration of healthcare services to urban areas, among others (Truter, Russell & Fary, 2014). A promising way of improving availability of rehabilitation is through telerehabilitation, which is a way of delivering rehabilitation services to clients through telecommunication networks and the Internet (Richmond et al., 2017). A significant advantage of telerehabilitation for the clients is that they do not need to travel to the therapy and hence saving both time and costs. Telerehabilitation can involve direct online communication with a physiotherapist but it can also mean a digital rehabilitation application providing automatic real-time help and guidance for the client (Capecci et al., 2018). The advantage of such applications is that the clients can decide themselves when they do the therapeutic exercises and it is easier to integrate the exercise into the daily activities (Salminen et al., 2019).

A promising and new way of implementing automatic real-time telerehabilitation services is through computer vision (CV) as the only technical equipment needed is one or more cameras and a computing device, such as laptop, tablet or smartphone. Tracking and analysis of human motions using CV has been an intensive research topic already for decades. Traditional CV based motion analysis uses marker-based approaches, involving installation of white dots or other reflective material on key points of the body, such as knee, ankle or shoulder joints. This limitation makes routine use of motion analysis systems impractical, as they require significant technical preparations prior to rehabilitation performance.

A significantly more practical and easy-to-use solution is CV based marker-less motion analysis, i.e. a solution where the application can identify and localize the key points of the human body without the use of physical markers (Coyler et al., 2018). Literature sources propose several generic marker-less motion analysis systems, typically utilizing emerging CV and machine learning-based techniques. These techniques are systems finding joint coordinates in a 2D space (Dang et al., 2019) and systems localizing joints in 3D space, typically multiple cameras, e.g. Pavlakos et al. (2017), but also single-camera 3D motion analysis systems are proposed, such as in Kanazawa et al. (2018). Considering practicality and user-friendliness, the optimal case, from a physiotherapy point of view, would be a single camera system capable of accurately finding the 3D coordinates of all joints. This would enable analysis of advanced joint movements, such as hip and shoulders analysis in functional movements like walking, stair climbing and squatting but also simple movements as arm or leg stretching and bending.

CV based marker-less 3D pose estimation from a single image view is though a challenging task. Development of such systems has hitherto mostly been for the entertainment domain, but some systems exist also for sports and rehabilitation. A general issue of current marker-less motion tracking systems is the difficulty to achieve sufficient accuracy, (Colyer et al., 2018, Pavlakos et al., 2018) and such systems are therefore not widely used within rehabilitation.

To be able to integrate CV in rehabilitation, the assessment that a physiotherapist execute must be valid and reliable to be objective (Mani et al., 2017). The use of CV in

rehabilitation supports the clients and helps physiotherapists assessment of movements that the client is performing. The expected visual and verbal output of the application is the most important thing for enabling it to measure and analyze movements correctly like a physiotherapist. (Rybarczyk et al., 2019) When this is the case, the application can be implementable in the rehabilitation process.

In clinical work for example in hospitals, physiotherapists use universal goniometers to measure their clients´ joint angles to evaluate the progress in rehabilitation. Valid goniometric measurements are central information for physiotherapists clinical decision (Reissner et al., 2019). If a physiotherapist does not have correct placement of the goniometer fulcrum over the center of rotation of the joint or wrong anatomic structures, variation in clinical joint angle measurement will emerge (Mohsin, McGarry & Bowers, 2018). It has been shown, that the variation can be up to 7 degrees from the actual degree in manual joint measurements with a universal goniometer (Reissner et al., 2019).
These potentials and challenges provided the motivation for performing a deeper analysis of the potential of CV-based marker-less pose estimation solutions for rehabilitation and to investigate how CV applications can be trained to detect human joints, in both a 2D and 3D space, without the use of physical markers. This would form a solid ground for developing easy-to-use and cost-effective digital aids for rehabilitation.

This paper provides an overview of an interdisciplinary research project (CV Rehab) at Arcada University of Applied Sciences, involving students, teachers and researchers from engineering, social- and welfare sections collaborating in designing, developing and testing new CV-based marker-less prototype applications for rehabilitation needs. In such projects, professionals and students need to critically analyze, create knowledge and come to conclusions based on the development work. As Elisabeth et al. (2009) has point out higher education has to train students to become skilled with this kind of interdisciplinary work both in scientific and professional environments. Interdisciplinarity helps multifaceted research project to understand and synthesize knowledge from different disciplines. (Elisabeth et al., 2009)

The purpose of this paper is to describe the development process of a CV-based marker-less prototype application measuring the knee angle of a client. Preliminary performance results of the prototype application are presented as well as experience and outcomes from this interdisciplinary project from an educational point of view.

2 METHODS

For the development, implementation and evaluation of the CV prototype the CeHRes Roadmap (fig. 1) was used as a guideline. This method consists of five intertwined phases and connecting cycles, including contextual inquiry *(solution for a relevant issue),* value specification *(points for improvement),* design *(development of technology/ CV prototype)*, operationalization *(actions for introducing the technology in intended context)* and summative evaluation *(influence on healthcare or related process)* (Kelders et al., 2018). The method has assisted our interdisciplinary team in planning, coordinating and executing the development process. So far, we have focused on phase one to three.

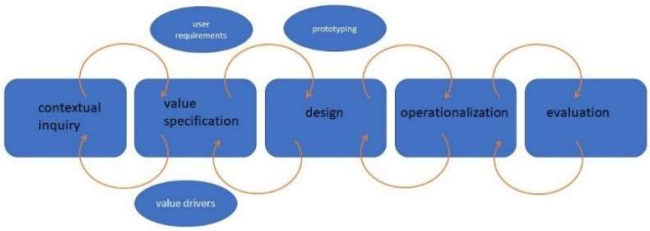

Figure 1: Modified CeHRes Roadmap (Kelders et al., 2018).

Planning, development, testing and evaluation of the CV prototype have been done in close collaboration between bachelor students, lecturers and researchers from the information technology and physiotherapy study programmes. The angle measurement accuracy of the prototype applications has been evaluated by comparing the measurement results with manual measurements performed by physiotherapists. Standard written principals of goniometer range of motion measuring, by Berryman Reese and Bandy (2010), have been followed when manually measuring the knee angel.

3 DEVELOPMENT PROCESS AND RESULTS

A CV-based marker-less solution for measuring the knee joint angle was developed fulfilling the requirements specified by physiotherapy professionals. In this case the requirements were straight-forward; 1) the maximum error tolerance is ± 5 degrees 2) the application must work on a standard laptop with a standard web camera. The technical development was started by critically analyzing the potential of current marker-less pose estimation solutions for rehabilitation applications. The evaluation revealed that some marker-less computer vision based techniques already provide sufficient accuracy for some rehabilitation services, especially OpenPose (Cao et al., 2019) and DensePose (Güler, Neverova & Kokkinos, 2018) for localizing human joints in a 2D space. Both solutions use a convolutional neural network (CNN) and supervised learning for training their model to recognize key points of the body. OpenPose uses the Max Planck Institute for Informatics (MPII) dataset (Andriluka et al., 2014) for training, consisting of 25 000 images and 40 000 people with annotated body parts, while DensePose uses the Common Objects in Context (COCO) dataset (Lin et al., 2014) which is similar to MPII. OpenPose is a popular multi-person pose estimation system which has also been used as a base for some of the most recent 3D pose estimation solutions, e.g. Shere, Kim and Hilton (2019). Though, in Cao et al. (2019) some weaknesses related to the input fed to the CNN have been identified. In OpenPose, the whole image, including one or more persons, is fed to the CNN while in DensePose a person in the image is first identified and extracted. Hence, OpenPose tend to cause some false positives and some key points of the body are lost under certain circumstances.

However, due to the popularity and documented accuracy of OpenPose it was chosen as the base technology for developing the original knee angle measurement prototype application. The joint detection techniques of OpenPose were reused and functionality for measuring the knee angle based on the locations of ankle, knee and hip joints was

added. The technical and clinical performance of this prototype was tested for certain knee angles (0°, 60°, 90°, 120°) and in functional movements. Eight persons participated in a standardized setup performed by physiotherapy students. The results indicated some weaknesses leading to inaccurate measurement results. The main flaw of the prototype was its inability to accurately detect all key joints (ankle, knee and hip) under certain circumstances, especially for high knee angles (> 110°), i.e. when the hip and ankle joints were located close to each other.

Based on the results and feedback by the physiotherapy student group about the technical performance an improved prototype based on DensePose was developed. Again, the joint detection capabilities of DensePose were fully reused and knee angle measurements added, in a similar fashion as in the previous version based on OpenPose. A screen shot of this prototype is shown in fig. 2, where the key points identified are X, Y and Z, i.e. the hip, knee and ankle joints. The knee angle alpha is then calculated applying the law of cosines.

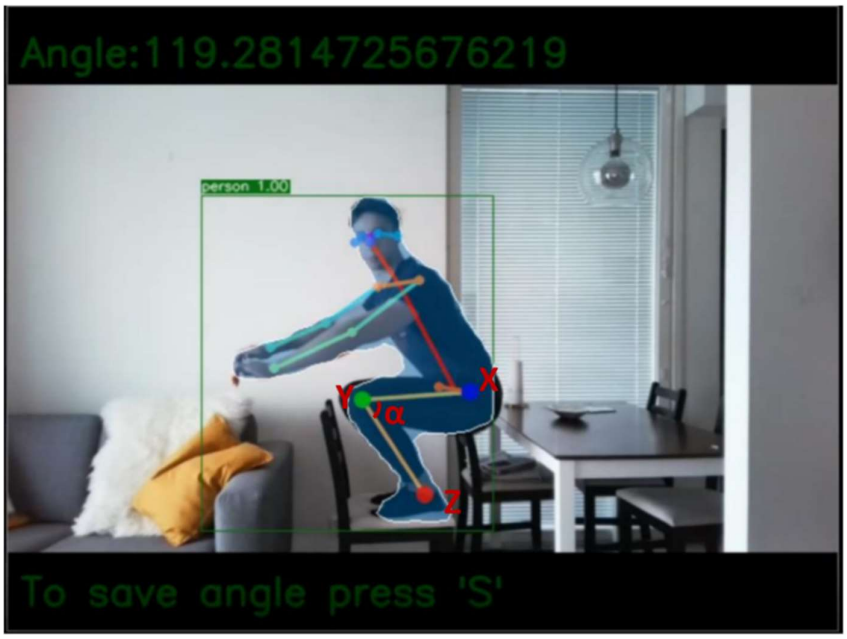

Figure 2: A screen shot of the knee angle measurement prototype application.

Preliminary tests, indicate that this new version is able to fulfill the measurement requirements at least for the 60°, 90°, and 110° angles. Though, the improved prototype version still needs to be rigorously tested by physiotherapy students under the same standardized conditions used for testing the original version.

Even though the development of this prototype is still in progress, it can be stated that the process has so far been a success. The prototype has shown promising measurement performance and the way the modified CeHRes Roadmap (Kelders et al., 2018) has been implemented during the development process, shown in fig. 3, turned out to be successful.

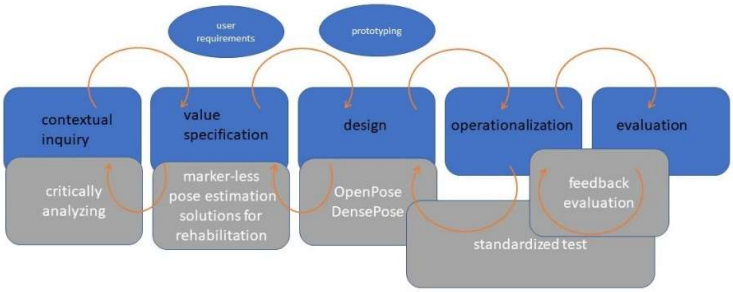

Figure 3: Development process of Computer Vision-based marker-less Real Time motion analysis for Rehabilitation.

The knee joint angle measurement application prototype is based on joint localization in a 2D space, meaning it can only analyze simple movements like flexion and extension for example in knee, ankle and elbow joints. Therefore, another prototype has been under development, which localizes joints in a 3D space and thus provide the possibility to perform movement analysis of more advanced joints, including hips and shoulders. This prototype is currently under development and the goal is to test and evaluate its performance in the near future.

4 EXPERIENCE AND OUTCOMES FROM AN EDUCATIONAL POINT OF VIEW

Students, teachers and researchers have gained valuable experience from driving an interdisciplinary research and development project of this magnitude. Research group members from the physiotherapy sector have gained practical insight in how technology can be used for providing rehabilitation services and engineering students as well as teachers have got a better understanding of the field of physiotherapy and what kind of applications rehabilitation services could benefit from and what the performance requirements are.

The digitalization is strongly growing in the health care sector along with an increasing volume of clients and the fact that the budget is strained for the health care sector. Before new digital solutions are implemented in clinical work it is important for the professionals to understand that the solutions have to be critically analysed to ensure whether as planned. In development well-coordinated and working interdisciplinary teams are productive, because the professionals can point out the benefits and barriers in development, implementation, evaluation and use in practice. In the CV Rehab project both professions bring their own competences in the development work for a user-friendly and well working digital solution.

The research activities have so far led to bachelor theses that involved students from the physiotherapy (Mishima, Berg, 2020, Sandell, Nars, 2020) and engineering (Grunér, 2020) program and also master thesis in the engineering program that has not yet been published. The interdisciplinary work has involved bachelor, master and doctoral students and the research group has published peer review scientific papers.

The CV Rehab project has also contributed to improved quality of big data analytics, information technology and physiotherapy education at Arcada. From the engineering point of view, it has been a cyclic process where third year students get basic skills in a CV course which is a part of the information technology curriculum. Students interested in digging deeper into the subject have, after completing the CV course, participated in the research project. Then, valuable knowledge, experience and research results have been utilized in the CV course to further develop its content and quality. Furthermore, the CV Rehab project has also led to increased study motivation in the CV course as the students get aware of and are informed about the possibility to continue with a real world project upon passing the CV course. Also, in the physiotherapy program the CV Rehab project has led to implementation of telerehabilitation in clinical courses where the students practice the use of digital healthcare equipment in controlled simulation scenarios but also with real clients. It is also notable both sectors have through this project learned in practice how to understand and communicate with each other which is very important for students when entering the professional life.

5 CONCLUSION

Easy to use telerehabilitation services from a user perspective is a real challenge for the digitalization of today's healthcare services. A promising way of implementing automatic real-time telerehabilitation services in the future is through CV as the only technical equipment needed is one camera and a computing device, such as smartphone. CV based marker-less pose estimation systems are attractive for rehabilitation aid applications as they can provide analysis and supervision of rehabilitation exercises for clients at home and thus reduce costs and the need for physically meeting the healthcare professionals. A significant challenge with such systems, though, is the accuracy and reliability of joint localization and active movement analysis.

An interdisciplinary research group was founded, involving students, teachers and researcher from the physiotherapy and information technology disciplines, for analysing the potential of CV-based marker-less motion analysis in digital rehabilitation services. Preliminary research results indicate that some recent CV based marker-less pose estimation systems already provide sufficient accuracy for joint detection and localization in joint angle estimations. A prototype application automatically measuring the knee angle has been developed and preliminary test results indicate that it can provide sufficient accuracy for this particular purpose.

However, further critical analysis of the benefits and barriers is still needed before CV-based marker-less motion analysis solutions can be widely implemented in physiotherapy. Strong interdisciplinary collaboration among students, teachers, researchers, and

professionals from different disciplines is required. An important goal for higher education is to train students to become skilled with interdisciplinary work both in scientific and professional environments. Interdisciplinarity and the modified CeHRes Roadmap has been a helpful framework in this multifaceted research project to understand and synthesize knowledge from different disciplines in the development process of CV based marker-less telerehabilitation. The project has provided valuable knowledge and experience for improving the quality of our teaching skills in interdisciplinary work as well as of our profession-specific education at Arcada.

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