Final report

Research grant entitled Gait analysis system for detect of pelvis and hip joint motion (grant No. K115894) starting from 1st February 2016, ending 31st July 2021.

I. Introduction

Motion analyses play an increasingly important role in injury prevention, examining the effect of joint malfunctions on gait and motion and modeling human posture and movements. Budapest University of Technology and Economics has a leading role in educating and training engineers; moreover, several university organizations are involved in fundamental biomechanical research topics such as motion analysis. This research aimed to develop a universal motion analysis procedure suitable for analyzing the impact of orthopedic injuries, malfunctions of the locomotor system, and the effect of surgical and conservative treatment. With the help of the resulting database, it is possible to make a diagnosis, select the appropriate treatment (operative or conservative), and follow up on the patient's recovery.

During the six years of the research, *experimental biomechanical investigation and numerical analysis were carried out* mainly. *In vivo motion analysis* was performed in the Motion Laboratory of the Department of Mechatronics, Optics and Engineering Informatics, BUTE.

II. Results presentation by research areas

Development of a gait analysis system (measuring method and processing software package) based on the use of depth sensors, suitable for determining the kinematic (distance, time, and angle type) and kinetic parameters of gait

The optical-based OptiTrack camera system available in the Motion Laboratory of the Department of Mechatronics, Optics and Engineering Informatics (BUTE) is significantly cheaper than the systems used in most scientific research (e.g., VICON or Qualisys). Due to the affordable costs of the system is started to be used for scientific purposes. In addition, this system is widely used for games' animation and telemetric tasks with a sensor placed on special clothing and anatomical points. *A primary purpose of our research was to investigate the usability of the system for gait analysis. The main research steps were: a detailed literature review [7]; development of a geodetic method to verify the available camera type (Flex13), the numbers of the cameras (18), and the camera layout [7]; determination of the system's scaling error [5,10]; creation of a marker cluster-based method to reduce the measurement errors from skin movement and avoid overlaps; exploring the most important factors that influence the accuracy of anatomical point calibration [16-18, 25]; development of a measurement control program (MOGI Universal BioMechanical Analyzer, MUBMA).* The related studies were performed on healthy individuals of different ages; orthopedic specialists were also consulted in some cases. One of the significant elements of data post-processing is signal processing since the commonly used filtering procedures are outdated and may be improper on some data sets. *The proposed filtering method takes into account the step frequency of the subject so that the cutting*

frequency used in the filtering can be customized. This leads to an advanced noise reduction with less distortion of the original signal [15].

Another important research area during the development stage was to find a low-cost motion capture system. Because of the favorable price, a system with depth sensors seemed to be the most suitable for this purpose; however, preliminary experiments have shown that the accuracy of angular parameters is inadequate. *Thus, the research focused on developing a motion capture system that uses a single action camera (i.e., GoPro) with augmented reality (AR) markers. The validation of the developed measurement method proved that the system could be used with sufficient accuracy to determine the gait parameters.* The essence of the method is that the AR markers correspond to the marker clusters used in traditional optical-based motion analysis, so the previously used measurement control programs can be used. The scaling methods using the spatial position of the anatomical landmarks and the post-processing procedure of the traditional method can also be used with the AR markers [6,22].

Gait measurements and the evaluation of the results on young and elderly people, people with various musculoskeletal disorders and injuries were continuously carried out. Based on the results, it can be stated that the gait parameters are of the same order of magnitude as the results found in the literature. Moreover, the parameter change between the different measurement groups is also in accordance with the literature. As an additional result of the data set development, *by applying the developed and validated full-body model, analysis of sports movements (such as running or dancing) can also be performed. The motion analysis can be supplemented with sports physiological measurements, stabilometric tests, ground reaction force measurements, EMG measurements, or thermal imaging measurements* [1,2,4,11,12,23].

On the other hand, in the case of injuries related to the pelvic girdle, it is crucial to analyze the spine's shape to determine the angles and curvature of the spine. By involving the motion analysis system and the self-developed control program, a non-invasive measurement method was developed and validated, which determines the spinal curvatures. The procedure was applied to examine athletes and children with scoliosis and bad posture [20,24,26].

Development of intelligent treadmill for gait analysis, serving for therapeutical and rehabilitation purposes

The aim of this development was to control the speed of the belt during walking or running by the examined subject in the case of a commercially available treadmill. This would allow the subject not to move at a prescribed (forced) speed but at a speed they feel comfortable with. The treadmill's engine has been modified accordingly. Unfortunately, after the control design process, the system showed that the speed changes were not properly smooth, a significant time delay appeared. *The effect of time delay can be reduced with GoPro cameras, but in the case of accelerating movements, the speed can only be increased intermittently. Thus, development was suspended with the help of a dedicated high-speed camera the delay could be reduced more successfully.*

Analysis of the effect of various types of treatment modes of fracture of the femoral neck by motion analysis

Patients from Péterfy Sándor Utcai Hospital-Clinic and Trauma Centre were involved in the study. *The research steps were the following: the exploration of the types of surgeries widely used in clinical practice (unilateral screw-fixed femoral neck fractures or hip prosthesis-replaced fractures and fractures involving the anterior and posterior pelvic ring); setting of inclusion and exclusion criteria for the participating patients; establishment of measurement groups (under 65 years, between 65-75 and 75-80 years, over 80 years); development of the measurement protocol, with appropriate (cloud-based) data management; selection and digitalization of scores to evaluate the lower body joints' condition (e.g., Pholemann score, Harris Hip score).* In the case of a traumatic injury, a preoperative examination cannot be performed; moreover, due to the nature of the measurement test (walking on a treadmill), the examination can only be completed one year after surgery. *The evaluation of the acquired scores drew attention to the fact that the number of falls in the postoperative period increases significantly, so the gait analysis should be supplemented with an analysis of different balancing abilities*. With the help of static posturography (stabilometry), the static balancing ability of the patients was analyzed, for which *17 independent and reliable parameters were selected from all the previously published parameters in the literature*. The independent and sensitive parameters contain time- and distance-related parameters and frequency parameters as well. The independence and reliability of these parameters were examined via further statistical analysis [8]. In addition to stabilometry, the so-called sudden provocation test is suitable for examining the dynamic balancing ability. *To characterize the dynamic balancing ability after a sudden change of direction, the previously used parameter (Lehr's damping ratio) was supplemented with new parameters (balance recovery time, directional ratio)* [14]. This dynamic balancing test seems to be suitable for all measurement groups to assess their balancing ability.

Preliminary stabilometric measurements showed *that the ankle- or hip-dominant balancing strategy changes after surgery*, and the head movements might also be involved in compensation [21]. These changes should be examined by analyzing the movement of the subject's body. In balancing tests, the human posture can traditionally be modeled as a single point (center of mass or center of pressure), or as a single or two degrees of freedom inverted pendulum. As the complexity of the model increases, its sensitivity increases; however, the uncertainties also increase. When selecting the appropriate model for a given balancing task, it should be ensured that it is sufficiently detailed to draw the necessary and correct conclusions, and at the same time, a sufficiently simple measurement method corresponds to it. In the case of bipedal upright stance, the so-called ankle-hip strategy approach distinguishes three strategies: ankle-dominant, hip-dominant, and mixed strategies. A biomechanical model should be used to examine the related coordination pattern that describes the motion in all directions and can also estimate the active muscle force or joint torque that creates the motion. *During our studies, a four degrees of freedom (DoF) double-inverted pendulum model was used*. With the help of this complex model, it was possible to

analyze the contribution of each joint through the balancing tasks. The four DoF models separately handle the ankle and hip joints and distinguish between forward-backward and lateral motion coordination. The model was validated by involving young, healthy individuals [15].

As an additional result of the developed stability measurement protocol, stability measurements were also carried out involving children with flatfoot and bad posture. Based on the results, it can be concluded that the load between the two sides is different from that of healthy children [9,19]. Moreover, stabilometric studies were performed to investigate the effect of fatigue on balancing ability in dancers [4].

III. Research participants

In this research project, the research team consisting of engineers and physicians has been set up for resolving the tasks specified in the research plan. The personal composition of the research team had been determined by the types and interconnections of the tasks to be resolved. Within the assignment set, each participant had their personal tasks to complete based on earlier research results and experience. In the case of student and doctoral student applications, we strived to give a task corresponding to their knowledge and previous research experience; moreover, the development of individual talent was a primary purpose.

IV. Benefits of research

One of the main goals of the research was to develop a biomechanical - mainly motion analysis-based - research method, which is suitable for the analysis of the postoperative effect of traumatic orthopedic injuries. The geodetic-based authentication procedure developed for the OptiTrack system has brought a new approach to validating motion analysis systems [5,10]. Analyzing the main error sources of the anatomical landmark calibration procedure, it was established that the so-called quality of the calibration and the results of the entire examination depend on the experience of the personnel and the nature of the anatomical landmark's location. Based on these findings, the comparability of calibrations performed by a different executive person can be questioned [16 - 18,25]. The proposed filtering method takes into account the step frequency of the subject so that the cutting frequency used in the filtering can be customized. This leads to an advanced noise reduction with less distortion of the original signal [5].

Applying the alternative AR marker and GoPro action camera as a motion capture system is a sufficiently accurate and low-cost method, which is also compatible with the developed measurement control program (MUBMA) and the previously used post-processing software (e.g., OpenSim) [6,22].

Score-based condition surveys of traumatically injured patients drew attention to the fact that the examination of balancing abilities during rehabilitation is essential. Seventeen independent and reliable parameters were identified and used to analyze the static balancing ability during stabilometric measurements [8]. In addition, in the case of the sudden provocation tests, the previously used parameter (Lehr's damping ratio) was supplemented with new parameters (balance recovery time, directional ratio) in order to better characterize the dynamic balancing ability [14]. To identify a balancing strategy (ankle-dominant, hip-dominant, or mixed), it is no longer sufficient to analyze the movement of the platform, but to record and analyze human movement (i.e., via the four degrees of freedom double pendulum model). The model made it possible to analyze the contribution of the main joints (hip, ankle) to the balance recovery motion [13].

Besides the traumatic orthopedic injuries, the results of this present research (modeling, development, and verification of measurement methods, verification of their reliability) can also be used for risk assessment of other orthopedic injuries, i.e., they are general.

Research areas related to gait analysis and reliability analysis is summarized in a defended Ph.D. dissertation (Gergely Nagymáté) [27], while the modeling methods used for analyzing balancing ability and its results are summarized in a submitted (successful home defense) Ph.D. dissertation (Bálint Petró) [28]. Currently, two of the involved students (Kristóf Rácz and Zsófia Pálya) are Ph.D. doctoral students, so this research project also played an important role in talent support and selection of talented young scientists.

Published articles (international journals):

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[13] Petró, B., Kiss, B., & Kiss, R. M. (2019). Analyzing human balance recovery action using calculated torques of a double pendulum model. *MATERIALS TODAY: PROCEEDINGS*, *12*, 431–439. http://doi.org/10.1016/j.matpr.2019.03.146

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Related PhD dissertations:

[27] Nagymáté G: Stabilometric parameter analyses and optical based motion analysis. Pattantyús-Ábrahám Géza Doktori Iskola, Budapest, 2019. (defended)

[28] Petró B: Human standing dynamic balancing and elementary biological signal processing. Pattantyús-Ábrahám Géza Doktori Iskola, Budapest, 2021. (submitted, successful home defense)