Application, Testing and Development of New Infocommunication Technologies in Rehabilitation

Abstract of PhD Thesis

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INTRODUCTION

E-health and telerehabilitation are increasingly important, which has been strengthened by the COVID-19 pandemic. In Hungary, there is a great need to optimize the healthcare infrastructure and eliminate the difficulties arising from geographical and specialist shortages, which ICT tools can support in the cases of prevention; treatment/rehabilitation; care of chronic diseases and palliative care.

Remote rehabilitation of the locomotor system can be implemented most effectively and efficiently using movement analysis. Maintaining balance and postural stability are fundamental elements of human body movement, which can be affected to varying degrees by disruption of the visual and vestibular systems.

In addition to traditional methods of marker-based movement analysis, portable mHealth devices with various built-in sensors – such as smartphones and smartwatches – can now be used to continuously monitor the health parameters of chronic patients to maintain care.

Besides the gold standard marker-based motion analysis, marker-free motion analysis is increasingly gaining prominence, as its advantages include that a specially constructed lab or studio is not required for data acquisition, and tracking of motion becomes unobstructed by the body being able to move freely in space. The preparation of data acquisition is also simplified and accelerated by omitting the step of placing markers. The latest marker-free pose estimation systems are artificial intelligence-based, deep learning-based software, among which the OpenPose software is one of the best known.

OBJECTIVE

In this dissertation, I present the results of 3 scientific studies. Over the past years, my research goals have been:

1. to examine the importance of visual feedback in postural stability and balance
2. to examine the longitudinal effect of visual feedback on the accuracy of gymnastic exercises using smart devices (marker-based movement analysis)
3. to examine artificial intelligence as a marker-free movement analysis option

The following hypotheses were formulated in the dissertation:

1. Based on the nature of the long-term sports activity, there is a difference in the reliance of individuals on visual and vestibular stimuli for maintaining balance.
2. The numerical visual display of limb displacement during gymnastic exercises improves the accuracy of the exercises.
3. The goniometer application running on the smartphone, paired with mirroring technology, can be used as a special sensor to monitor the correct execution of gymnastic exercises.
4. The new application layer of the OpenPose artificial intelligence-based, marker-free human position estimation software capable of

numerical display shows close agreement with the measurement results of the Kinovea system.

METHODS

<u>The first study</u>

In our study, we examined 40 women, 20 of whom practiced sports where rotating and twisting movements are dominant (Dominant group (D): gymnastics, figure skating, ballet, dance) and 20 practiced sports where these movements are not dominant (Non-Dominant group (ND): volleyball, rowing, running). The average age of group D was 22.51 ± 2.66 years, height 1.66 ± 0.05 meters, body weight 54.06 ± 6.04 kg and BMI 19.71 ± 1.92. The ND group had an age of 22.23 ± 1.99 years, height of 1.68 ± 0.06 meters, body weight of 59.80 ± 7.83 kg and BMI of 21 ± 2.76. The participants were members of the Hungarian University of Sports Science, the Hungarian State Opera House, the Hungarian Dance University and the Budapest Dance Theatre. The participants' athletic training was either high (training at least 3 times a week, regular competition participation) or professional level (paid sports activities/theatre performances).

In our study, stabilometric measurements were performed using a MatScan platform [MatScan Research ver. 6.85-26, Tekscan Pressure Measurement System (307 West First Street South Boston, USA)]. Participants were instructed to stand barefoot on the platform with feet together and arms held forward at shoulder height for 20 seconds each, first with eyes open (EO), then with eyes closed (EC).

Next, to disrupt the vestibular system, participants were rotated 10 times in a floor-mounted rotating chair. The rotation speed was controlled by a metronome (cycle time T = 2 sec). Immediately after the rotation, participants stood on the platform for 20 seconds with eyes open (REO), followed by another 10 rotations and a 20-second trial with eyes closed (REC). During data collection, we recorded four types of center of pressure (COP) movements: anterior–posterior (A–P), left-right (L–R) sway, total COP path length (Distance), and COP area (Area). Participants wore comfortable sportswear throughout the measurements.

Normality was checked using the Shapiro–Wilk test. A two-sample t-test was used to compare personal data between the two groups, and a mixed-design ANOVA was applied to analyze group effects. When significant main effects or interactions were found, group differences were identified using Tukey's HSD post hoc test. Effect sizes (Cohen's d) and statistical power were also calculated. All analyses were performed using Statistica 12 software, with statistical significance set at $p < 0.05$.

The second study

A total of 140 participants took part in the study. They were assigned to two experimental groups—young adults (50 participants: 32 women, 18 men; age 25.6 ± 3.1 years) and older adults (50 participants: 37 women, 13 men; age 74.8 ± 9.1 years)—and two control groups—young adults (20 participants: 12 women, 8 men; age 26.25 ± 3.6 years) and older adults (20 participants: 13 women, 7 men;

age 70.15 ± 5.2 years). The study was approved by the Research Ethics Committee of the Hungarian University of Sports Science under approval number TE-KEB/18/2021.

Before the study, members of the experimental groups were required to learn how to use the screen-sharing function, which allowed them to monitor their performance during the exercises by observing joint movement on their computer screen. Joint angles were measured using the Angle Meter goniometer application running on a smartphone. For the squat exercise (baseline movement), the target angle of movement was set at 65°, and for the knee-lift exercise (balance task), at 75°. For safety reasons, older participants were allowed to hold onto a chair during the exercises in both tests. The computer or laptop was positioned at eye level. The smartphone was attached to the outer side of the participants' right thigh using a phone-holder strap (Figure 1).

Figure 1. Demonstration of the squat and knee-lift exercises performed with a smartphone attached to the limb, shown by one participant from the older and one from the younger experimental group.

In the first week of the study, we asked the participants to perform the previously practiced movements 15 times a day, without external assistance, at home. After one week, we performed control measurements, where the participants still could not see the thigh angle positions achieved during the exercises (measurement 1). The members of the control groups practiced using the goniometer application and screen sharing similarly to the first week, and the members of the study groups practiced for another 2 weeks, with weekly control measurements (measurements 2 and 3). After three weeks, we asked the participants to evaluate the use of the self-monitoring technology, where 1 indicated easy usability and 5 indicated very difficult usability.

During the exercises, the measured deepest thigh angle was compared to the target angle and the absolute value of the difference was calculated. Normality was checked with the Shapiro–Wilk test. Taking into account repeated measures, a mixed-order factorial ANOVA was used, with Tukey HSD post hoc test in case of significance. In addition, the effect size (Cohen d) and statistical power were calculated. The analyses were performed with Statistica 12 software. A significant difference was defined at a value of $p<0.05$.

The third study

Our research group created an application layer that can extract the time series of angles of arbitrary body parts using the output coordinates of the OpenPose human position estimation artificial-based software, even using two cameras simultaneously. The study was approved by the Ethics Committee of the Hungarian University of Physical Education and Sport Sciences under the registration number TE-KEB/07/2023. During the study, three of our co-authors performed 10-10-10 squats, a total of 30, which were recorded with a camera (Figure 2). After that, for each squat, we determined the angle of the thigh with the lower leg, expressed in degrees, compared to the standing position (180 degrees), using Kinovea and the OpenPose software supplemented with the software layer. For our statistical calculations, we used a paired t-test, during which we compared the joint angles measured by OpenPose and Kinovea. A significant difference was defined at a p value <0.05.

RESULTS

Results of the First Study

Dominant Group

With eyes closed, center of pressure (COP) displacement was significantly greater than in the post-rotation eyes-open condition in terms of Distance (92%; $P = 0.001$, $ES = 1.679$) and Anterior–Posterior movement (59%; $P = 0.041$, $ES = 1.315$). No significant differences were found between the EO (pre-rotation) and REO conditions.

Non-Dominant Group

With eyes closed, COP displacement was significantly smaller than in the REO condition for Left-right movement (90%; $P = 0.002$, $ES = 1.068$).

Under EO conditions, significantly better results were observed compared to REO in Area (176%; P = 0.010, ES = 0.714), Distance (80%; P < 0.000, ES = 1.352), Anterior–Posterior movement (83%; P = 0.002, ES = 1.388), and Left-right movement (90%; P < 0.000, ES = 1.590).

Comparison of Dominant and Non-Dominant Groups

Differences appeared between the dominant (D) rotation-based athletes and the non-dominant (ND) non-rotation athletes under both visual feedback with vestibular disturbance (REO) and visual deprivation (EC) conditions (Figure 2).

During the REO condition, the ND group showed a larger COP displacement than the D group in Area (P = 0.030, ES = 1.270), Anterior–Posterior movement (P = 0.016, ES = 1.349), and Left-right movement (P < 0.000, ES = 1.400).

In the case of Distance, the movement of the COP of the D group during the EC and REC conditions was larger (P = 0.037, ES = 1.487 and P = 0.013, ES = 0.714) compared to the results of the ND group.

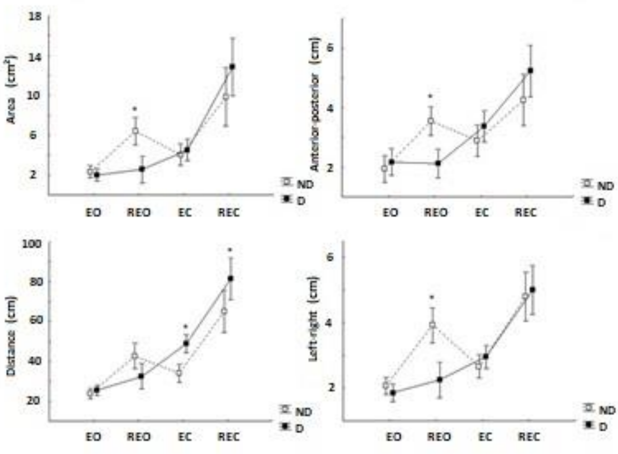

*Figure 2. Statistical comparison of the COP displacement results of the Dominant (D) and Non-Dominant (ND) groups with eyes open (EO), with eyes open after rotation (REO), with eyes closed (EC), and with eyes closed after rotation (REC). Significant differences are indicated by *.*

Results of the Second Study – Effects of Motion Tracking During Squat and Knee-Lift Exercises

Squat Exercise

Comparison of the First, Second, and Third Measurements in the Young Experimental Group

In the young group, the deviation values in the first measurement were significantly higher than in the second measurement (103%, $p < 0.05$, ES = 1.67), and also significantly higher than in the third measurement (449%, $p < 0.05$, ES = 2.22). The results from the second measurement were 122% higher than those from the third measurement ($p < 0.05$, ES = 1.1).

Comparison of the First, Second, and Third Measurements in the Older Experimental Group

In the older group, deviation values in the first measurement were significantly higher than in the second measurement (96%, $p < 0.05$, ES = 2.4), and also significantly higher than in the third measurement (124%, $p < 0.05$, ES = 2.31). No significant difference was found between the second and third measurements ($p = 0.07$).

Comparison of the young experimental and control groups

When comparing young adults' data, no differences were observed between the experimental and control groups in the first measurement. However, significant differences were found in the second (100.4%, $p < 0.05$, ES = 1.2) and third measurements (388%, $p < 0.05$, ES = 2.93). The control group showed significantly larger deviations from the target joint angles than the experimental group (Figure 3).

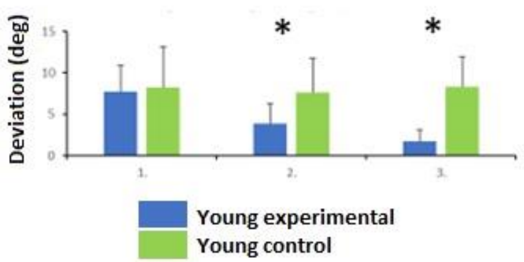

*Figure 3. Comparison of the experimental and control groups of squatting exercises in young adults. Measurement 1 was performed without one week of self-monitoring, and measurements 2 and 3 were performed after one week of self-monitoring in the experimental group. Significant differences (p<0.05) are marked with *.*

Comparison of the study and control groups of older adults

When comparing the results of older adults, there was no difference between the 1st measurements of the study and control groups, but a significant difference was found between the 2nd (63.8%, $p<0.05$, ES = 0.85) and 3rd measurements (139.7%, $p<0.05$, ES = 1.76). The deviation of the angular position values of the control group from the target value to be achieved was significantly greater than the results of the study groups (Figure 4).

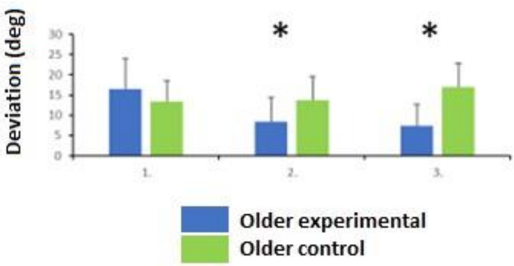

*Figure 4. Comparison of the experimental and control groups of squatting exercises in older adults. Measurement 1 was performed without one week of self-monitoring, and measurements 2 and 3 were performed after one week of self-monitoring in the experimental group. Significant differences ($p<0.05$) are marked with *.*

Knee-Lift Exercise

Comparison of the First, Second, and Third Measurements in the Young Experimental Group

In the young group, deviations from the target angle in the first measurement were significantly greater than in the second measurement (89%, $p < 0.05$, ES = 1.18) and significantly greater than in the third measurement (248%, $p < 0.05$, ES = 1.59). The deviation in the second measurement was 83% higher than in the third measurement ($p < 0.05$, ES = 1.23).

Comparison of the First, Second, and Third Measurements in the Older Experimental Group

In the older group, deviations in the first measurement were significantly greater than in the second measurement (52%, $p < 0.05$, ES = 2.36) and significantly greater than in the third measurement (131%, $p < 0.05$, ES = 3.16). The second measurement showed 51% greater deviation than the third ($p < 0.05$, ES = 1.31).

Comparison of the Young Experimental and Control Groups

When comparing the young adults' results, no differences were observed between the experimental and control groups in the first measurement. However, significant differences were found in the second (78.5%, $p < 0.05$, ES = 0.96) and third measurements (185%, $p < 0.05$, ES = 1.6). The control group showed significantly larger deviations from the target angle than the experimental group (Figure 5).

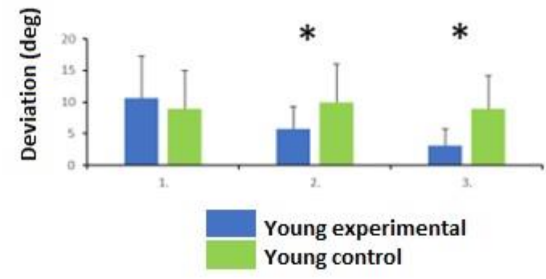

*Figure 5. Comparison of the experimental and control groups of knee-lifting exercises in young adults. Measurement 1 was performed without one week of self-monitoring, and measurements 2 and 3 were performed after one week of self-monitoring in the experimental group. Significant differences (p<0.05) are marked with *.*

Comparison of the study and control groups of older adults

When comparing the results of older adults, there was no difference between the 1st measurements of the study and the control groups, but a significant difference was found between the 2nd (68%, $p<0.05$, ES = 1.033) and the 3rd measurements (182.8%, $p<0.05$, ES = 2.01). The deviation of the angular position values of the control group from the target value to be achieved was significantly greater than the results of the study groups. There is a significant F-interaction between the study and control groups ($F = 167.4$, $p<0.05$), so we must assume a different trend between the study and control groups (Figure 6).

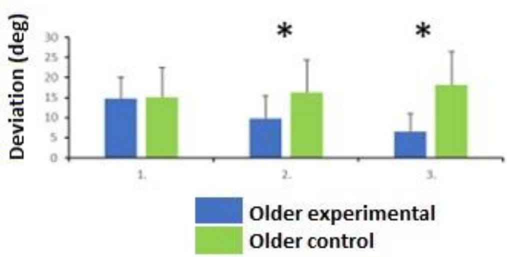

*Figure 6. Comparison of the experimental and control groups of knee-lifting exercises in older adults. Measurement 1 was performed without one week of self-monitoring, and measurements 2 and 3 were performed after one week of self-monitoring in the experimental group. Significant differences (p<0.05) are marked with *.*

Results of the third study

A paired t-test was used to compare the knee joint angle values measured by our OpenPose software and Kinovea software to determine whether there was a significant difference between the two measurement methods. The results showed that there was no statistically significant difference between the mean angle values measured by the two systems (mean difference = 0.33° ± 2.29°, P > 0.05), suggesting that the data provided by OpenPose reliably approximated the values measured by Kinovea (Figure 7).

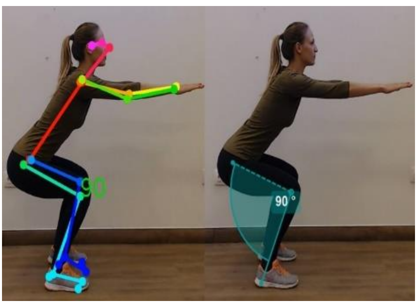

Figure 7. Comparison of OpenPose's new application layer and Kinovea software in the starting and squatting positions

CONCLUSIONS

The first study

Balancing requires the coordinated functioning of multiple sensory systems, and previous research suggests that athletes—especially dancers—achieve better balance performance due to their more developed body awareness. In our study, we compared athletes engaged in predominantly rotational and non-rotational sports movements. Our results showed that participants from sports involving rotational movements were less sensitive to disturbances of the vestibular system when visual information was available. This confirms earlier assumptions that dancers' postural control relies primarily on the availability of visual information due to mastered focusing techniques, and supports previous suggestions that the attenuation/blocking of signals from the central nervous system also contributes to this.

In contrast, in our other study group, where rotational movement is not characteristic, participants responded more sensitively to vestibular disturbances, which supports the notion of sport-specific differences in sensory processing. Based on our findings, different sensory-focused training methods can be recommended for individuals with diverse sports backgrounds; however, the conscious regulation of visual feedback is essential in all cases. For athletes requiring a high degree of dynamic and static balance, training that consciously limits visual input and incorporates multisensory, instability-creating exercises could be used as a supplement. Meanwhile, for those with other sports backgrounds, it is more advisable to use balance and proprioceptive exercises introduced gradually while maintaining visual information, before increasing vestibular load.

The second study

A wide range of technological solutions is now available for monitoring and analysing movement, and their application is of great importance in musculoskeletal prevention and rehabilitation. Previous research has already investigated whether physiotherapists can replace traditional joint range-of-motion measurements with smartphone-based goniometer applications, and this method appeared to be reliable. In our study, we extended the use of the goniometer application so that it was not the physiotherapist but the patient who applied it for self-monitoring, supplemented with screen mirroring. As a result, we confirmed the motor learning–enhancing effect of real-time feedback.

Before self-monitoring—during the first measurement—no significant differences were observed in either group, and deviations from the target angle were clearly visible in both the squat and high-knee exercises. This aligns with previous studies showing that, in the absence of supervision, exercise execution deteriorates. In contrast, targeted visual and numerical feedback produced significant improvement within just one week, which is consistent with earlier findings that visual feedback can reduce joint load and optimise movement pattern execution. Our study also supports research indicating that digital device use may pose greater challenges for older adults, though with appropriate support, it can be successfully implemented.

Overall, our results complement previous literature by demonstrating that substantial improvements in movement quality can be achieved using even affordable, widely accessible infocommunication tools—not only expensive, professional motion analysis systems.

The third study

A considerable body of previous research focuses on technologies specifically designed for medical purposes. Musculoskeletal rehabilitation can be complemented with motion-analysis–based assessment and follow-up, using either marker-based or markerless solutions. The latest technologies rely on artificial intelligence and machine learning. In our study, we selected the OpenPose software as a foundation—an open-source tool for real-time human body, hand, and facial movement tracking and keypoint-based analysis. While VICON, considered the gold standard in motion analysis, operates in 3D, OpenPose processes only 2D data; therefore, we enhanced the software by incorporating the simultaneous processing of data from two cameras. This enables motion observation in both sagittal and frontal planes.

This approach is advantageous partly because combining two camera views reduces the risk of certain joint keypoints being occluded—a major source of error in OpenPose, as confirmed by previous research. For software validation, we used Kinovea, another freely available, markerless tool that is widely recognised and applied. Based on our results, we concluded that the software is capable of providing numerical data on movement, and that—compared with Kinovea—there is no statistically significant difference in the measured joint angle values.

Decisions on the hypotheses

1. Based on the nature of the long-term sports activity, there is a difference in the reliance of individuals on visual and vestibular stimuli for postural stability and balance.

We accept the hypothesis. Our decision is supported by the fact that based on our results, we found that while the members of the group of athletes performing dominantly (D) rotating, twisting sports movements reacted more sensitively to the elimination of the visual stimulus, the members of the group of athletes performing dominantly (ND) rotating, twisting movements were more sensitive to the disruption of the vestibular system during balance maintenance.

2. Numerical visual display of limb movements during gymnastic exercises improves the accuracy of performing the exercises.

We accept the hypothesis. Our decision is supported by the fact that during our statistical analyses we obtained the result that the regular use of real-time, numerically expressed visual feedback significantly increased the accuracy of performing gymnastic exercises in the study groups.

3. The goniometer application running on the smartphone, combined with mirroring technology, can be used as a special sensor to monitor the correct execution of gymnastic exercises.

We accept the hypothesis. Our decision is supported by the fact that the smartphone attached to the body is able to measure the displacement in a given body part in degrees, the visual tracking of which improves the accuracy of the execution of the exercises.

4. The new application layer of the OpenPose artificial intelligence-based, marker-free human position estimation software capable of numerical display shows a close match with the measurement results of the Kinovea system.

We accept the hypothesis. Our decision is supported by the result that the OpenPose software, supplemented with an extra layer, did not show a significant difference with the Kinovea software commonly used in motion analysis based on the one-sample t-test during the examined exercises (Ave = 0.33 ± 2.29°).

LIST OF OWN PUBLICATIONS

<u>Original publications on the topic of the dissertation</u>

Zsarnóczky-Dulházi F, Lelbach Á, Rácz L, Kopper B. **(2020)** A digitális innovációk és infokommunikációs eszközök az időskori betegellátásban. Idősgyógy. 5(2-3):96-101.

Zsarnóczky-Dulházi F, Kopper B. **(2021)** Testhelyzet felismerő szoftver továbbfejlesztési lehetősége a hatékonyabb online mozgásszervi rehabilitáció megvalósulása érdekében. Rendvédelem (ON-LINE), X(1):122-134

Zsarnóczky-Dulházi F, Kopper B, Zsarnóczky M, Dávid LD. **(2021)** Civil szervezetek egészségformáló hatása a közösségimédia-platformokon keresztül. Civil Szemle, 18(1):27-40.

Zsarnoczky-Dulhazi F, Hegedus A, Soldos P, Trzaskoma L, Kopper B. **(2022)** Effect of sports background on the visual and vestibular signal processing abilities of athletes Science & Sports, 37(8):798.e1-798.e6. DOI: 10.1016/j.scispo.2021.12.005

Zsarnóczky-Dulházi F, Kopper B, Zsarnóczky M, Dávid LD. **(2022)** A közösségi finanszírozás helye és szerepe a mai társadalmakban, különös tekintettel hazánkra és az egészségügyi kiadásokra. Civil szemle, 19(1):41-56.

Zsarnoczky-Dulhazi F, Zsarnoczky M, Kopper B, Karpati J, Molnar Cs, Adol GFC, David LD. **(2023)** Promising European research results to improve hospitality in healthcare by eHealth,Int J Manag. 112: 1-5. DOI: 10.1016/j.ijhm.2022.103411

Zsarnoczky-Dulhazi F, Agod S, Szarka S, Tuza K, Kopper B. **(2024)** AI based motion analysis software for sport and physical therapy assessment. Rev Bras Med Esporte, 30. DOI: 10.1590/1517-8692202430012022_0020i

Zsarnóczky-Dulházi F, Lelbach Á, Rácz L, Trzaskoma L, Berkes I, Sümegi T, Kopper B. **(2024)** Okostelefon-szenzorokon alapuló technológia alkalmazása az otthoni gyógytorna eredményességének ellenőrzésére. Orv. Hetil, 165(7):265-273. DOI: 10.1556/650.2024.32974

<u>Original publications not related to the topic of the dissertation</u>

Zsarnóczky-Dulházi F, Zsarnóczky M. **(2018)** Az akadálymentes turizmus, mint rehabilitációs „eszköz”. Pintér Gábor. Arccal vagy háttal a jövőnek? LX. Georgikon Napok. ISBN:9789639639928 pp.56-61.