Literature review

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Optimising video-based data capture for pathological gait analysis in children with cerebral palsy using a limited number of retro-reflective cameras (literature review)

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This paper presents a review on the methodology used to enable capturing pathological gait data via clinical video analysis which is used in diagnosis and treatment of individuals with functional disorders of the musculoskeletal system. Available literature sources were used to formulate recommendations for researchers and doctors in clinical study of walking and gait. Main patterns of placement of passive markers used in the clinical analysis of the gait in children with cerebral palsy were described. It was found that the IOR model is optimal for clinical analysis of the gait in patients that have low walking speed using a minimal capture system configuration (6 cameras). The method of Oxford Foot Model is described which is able to reflect in detail the biomechanics of foot parts during walking.

Keywords: motion video capture, clinical gait analysis, cerebral palsy

INTRODUCTION

The study of human locomotor function is currently an independent scientific discipline, based on the integration of biomechanics, anatomy, physiology and neurophysiology, clinical medicine. It has been called "Gait Analysis" or "Clinical Gait Analysis. The "gold" standard for assessing the efficiency in the rehabilitation of motor functions and treatment of musculoskeletal system disorders is the use of video-based analysis systems of human motion kinematics which mainly apply the Motion Capture technology and are one of the most accurate methods up to date [1–5]. The test results of the Qualisys Systems (Sweden) showed that the average error for Oqus cameras was less than 0.15 mm for static tracking and 0.26 mm for dynamic tracking by spatial recording of objects [6]. Diagnosis with video-based analysis systems is carried out with optical infrared cameras, dynamometer platforms (Force plates) and wireless electromyography systems (EMG), which are able to accurately estimate the trajectories of movements, their amplitudes, energy expenditure, loads, power, muscle work, space-and-time characteristics and other indicators. This technology uses passive markers that are attached to certain anatomical points on the body which reflect infrared radiation. Thereby, the human skeleton is reconstructed and the data are analyzed and interpreted (**Fig. 1**). Data analysis can be developed individually or using existing Visual3D software (C-Motion, Inc.).

Systems using accelerometers and gyroscopes, such as Noraxon Lab, have been increasingly used in clinical practice. Such systems are very easy to adjust and use, and they are also able to quickly generate reports. However, this technology is subject to magnetic interference and, in cases of metal devices (prostheses, walkers, exoskeletons and other devices) tracking may become difficult.

Over the past 40 to 50 years, the rate of children born with cerebral palsy has not changed and is 1.5–3 children per 1,000 newborns [9, 10]. Analysis of walking according to the criteria of Edinburgh Gait Assessment [7] and video-based analysis have been recognized tools in clinical diagnosis in patients with cerebral palsy [8–10]. The analysis allows recording of angular deviations in the joints in all projections, which helps to analyze motor functions for a more accurate diagnosis. Further, the information is used to arrange a "list of problems" in which all gait deviations can be listed; classification of primary (neurological), secondary (age-related), and tertiary deviations (deformities) is performed; treatment tactics are determined [11].

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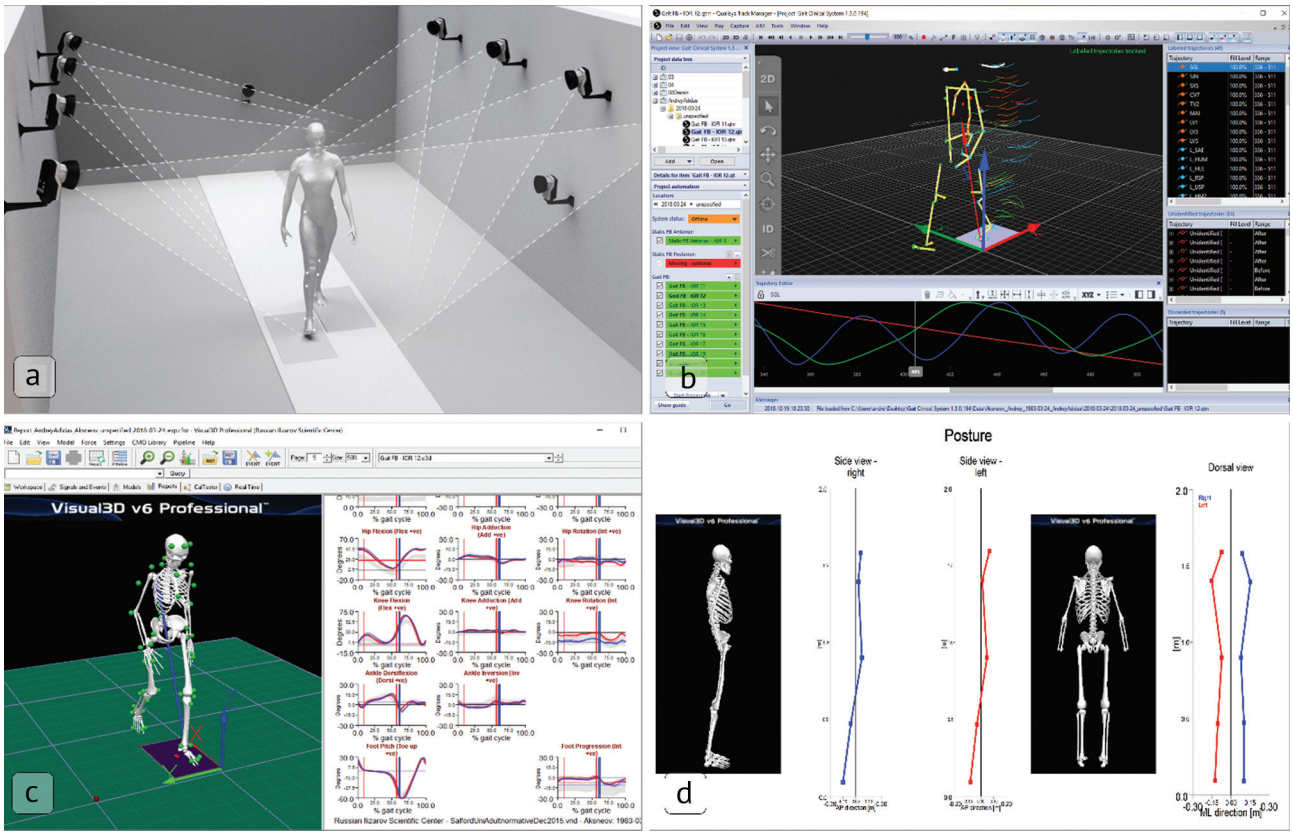

Fig. 1 *a* – Example of the Qualisys cameras (Sweden) location and force plates in the laboratory of gait recording; *b* – recording with QTM (Qualisys); *c* – analysis of walking with Visual3D (C-Motion); *d* – element of a clinical gait report (symmetry assessment in static position)

In the last decade, clinical biomechanical laboratories have been working on the development of a standard for the gait deviation index (Gait Deviation Index) and the walking index (The Gait Profile Score) for patients with cerebral palsy [12-14]. These indices are included in the clinical reports of biomechanics in most modern laboratories and are also included in the Qualisys standard gait report (PAF).

It is worth emphasizing that the price of a complete video analysis system, which includes power platforms, cameras and wireless EMG, is very high; therefore, clinical centers frequently purchase incomplete system kits, resulting in problems with developed Visual3D software (C-Motion, Inc.) for clinical gait analysis.

This article provides an overview of the main methods of video-based analysis and possible solutions for its use in clinical practice, discusses the main models, recommendations, and discloses some of the techniques that may influence the outcome of clinical biomechanic reports. Incorrect operation of the system and improper technique can affect the diagnosis and worsen the quality of patients' treatment and rehabilitation.

Technique of video-based analysis of biomechanics in clinical practice

Passive reflective markers are widely used in locomotion recording in most clinical video-based analysis laboratories. The use of such markers has several advantages due to their relatively small weight decreasing skin movements during locomotion as compared to active ones which have a LED and a battery. They are of various sizes to allow tracking the kinematics of movements in several joints of the foot in children and improve the accuracy of clinical diagnostic results [15]. The technique of video analysis implies mounting the markers on the anatomical points of the human body which reflect infrared radiation of high-speed cameras. If at least two cameras see a marker, its exact trajectory of movement in 3D space can be reconstructed with the help of special algorithms and calibration of the system [16].

Recording of patients' gait in clinical practice is carried out with a frequency of 100 Hz and a camera shutter speed of at least 1/250 seconds, which is sufficient to reconstruct the kinematics of joint movements without losing data [17]. Until recently, laboratories had to adapt premises for video analysis systems using dark colors, non-shiny surfaces and excluding direct sunlight. Modern video analysis systems use improved algorithms and adjust the system so as to operate in almost any conditions (**Fig. 2**).

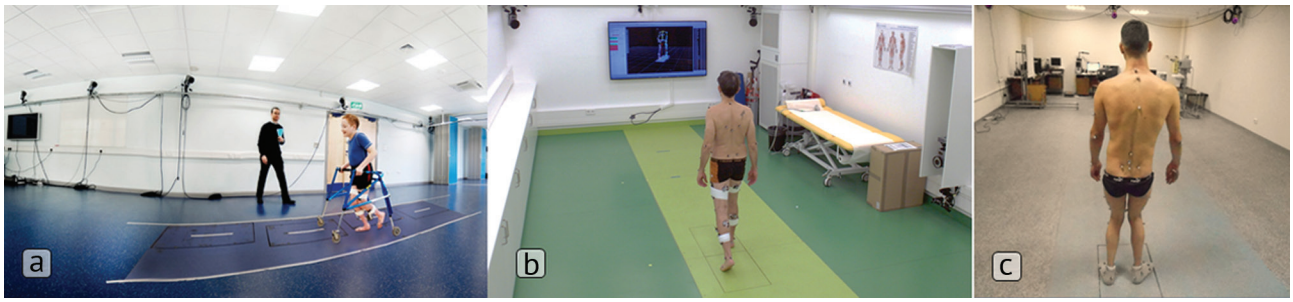

Fig. 2 Example of examinations in clinical laboratories of walking biomechanics: *a* – University of Salford, England; *b* – Olga Clinic, Germany; *c* – RISC for RTO, Ministry of Health, Russia

In clinical practice, video analysis allows comparing the indicators of kinematics, kinetics and electrical muscle activity. Kinematics is recorded using optical cameras. The main kinematic parameters used in clinical reports include the joint range of motion, angular changes of the joints and body segments in three planes, sagittal, frontal and horizontal (example: abduction, adduction, flexion, extension, dorsiflexion, plantarflexion, supination, pronation, varus and valgus, sagittal balance and others); speed and acceleration, linear changes, spatial-temporal characteristics of the gait (speed, cadence, length and width of the step, temporal characteristics of the step cycles and foot roll-over, and others) [18–22].

Kinetic data are indicators that use the parameters of power platforms. These include moments (for example, sagittal flexion / extension moment, abduction/adduction moment, foot pronation/supination moment, and others), muscle absorption/generation powers, foot roll over center, forces of support reaction (in three projections), forces of joint response, impulse and others [23, 24].

In modern laboratories, electrical activity of the muscles is recorded with wireless EMG systems, such as Noraxon (USA). Such systems have several advantages: they are compact and biomechanics of walking cannot be distorted as there no wires.

A very important element is the synchronization of the recording on all devices with a trigger that simultaneously starts the system.

Markers are placed on the patient's body before launching the system for subsequent reconstruction of the skeleton and data analysis. The choice of a marker model depends on the type of study. Data recording is performed until 5 to 10 steps have been recorded with only one of the limbs on the power platform. Processing of the data to formulate a conclusion is done with automated software or "manually." It should be noted that the biomechanics of walking can vary at different speeds. Orthopaedic shoes also have an effect on kinematic and kinetic changes [25, 26].

Main recommendations for conducting clinical gait analysis

A method which has been not well tested may affect the accuracy of the results in a clinical setting. There are general rules for working in video-based analysis laboratories and conducting diagnostic measures in a clinical setting. Sufficient space for recording the gait is important to allow the patient to accelerate gait and a normal comfortable pace of walking. Studies have shown that an uneven surface affects the work of the muscles, changes the angular characteristics of the joints, as well as kinetic data, so it is recommended that there are no irregularities in the patient's way [27]. Use soft color tones in the laboratory (bright color can affect walking, as well as distract the patient) and good lighting. Old people were slower if illumination was reduced, and patients with disorders of the musculoskeletal system showed significant changes in walking biomechanics [28].

Cameras are recommended to be installed on special holders under the ceiling. Calibration may fail and accuracy drop if cameras move (patient may touch). It is necessary to maintain a constant temperature of the air and the floor in the laboratory (low or high temperatures can affect walking, and high temperatures may affect the adhesion of markers and EMG sensors due to sweating of patients). It is important to prepare equipment and other devices for diagnosis before the patient arrives (so that he does not wait); it is recommended to give time to the patient to adapt in the laboratory so that he chooses a comfortable walking speed. Clinical laboratories of biomechanics have built-in power platforms in the floor that measure the kinetics (joint moments, forces of support reaction, foot roll over center, joint power, etc.), so you should find the optimal starting point for the patient to get at it without focusing on attention. It is recommended to send an information document to the

patient prior to the study so that he is familiar with the diagnostic method and gives his full consent (not every patient is ready to undress or, if there is a lot of body hair, consent to shaving to install the EMG electrodes). The patient must be warned to wear tight-fitting shorts for examination, or the laboratory must provide clothing for diagnosis. It is very important to record movements of the person's body and not clothes. A sufficient number of successful steps should be recorded (usually 5–10 for each leg).

Walking speed

One of the main tasks of clinical gait analysis laboratories is a comparative analysis, such as monitoring the recovery of motor functions during treatment. However, the effect of the walking speed factor showed significant changes in the results of kinematics, kinetics, and lower limb EMG [29–40]. Walking speed has a significant impact on overall posture as well as on the work of the gluteus, thigh and lower leg muscles [37]. The most significant changes in gait parameters were noted as soon as the subjects reached a walking speed exceeding their usual speed by more than 20 %. A decrease in speed leads to a decrease in flexion of the knee joint and a change in the work of its moment [31].

Therefore, a comparative analysis should consider the speed factor, and, in certain cases, it should be monitored. The results of numerous studies lead to the conclusion that the recommended range of speeds in the comparative analysis should not exceed ± 5 %. Otherwise, it will be difficult to determine what influenced the results by comparing, walking speed or the effect of treatment. Laser gates or clinical treadmills are used to control the speed in laboratories, which can also be built into the floor.

Phases of clinical gait analysis

The procedure of clinical recording of the biomechanics of movements in the laboratory conditions consists of the following steps: placement of cameras, adjustment of the recording system frequency, synchronizing cameras and other systems (EMG, power platforms, system for measuring plantar pressure under the feet, etc.), calibrating the system, the choice of data recording methodology and pattern of markers attachment, recording, processing of results, and an issue of a clinical report [17].

In order to analyze the kinematics and kinetics of the trajectories of the markers, it is necessary to determine the human segments for accurate registration of the rotation of joint centers. Errors in identifying the segments can be due to incorrect determination of anatomical points and attachment of markers on them; errors can occur if markers are adjusted by different people, or due to incorrectly chosen markers or skin movements [41–46]. Results of the studies conducted in the early 2000s may differ from the results obtained using more advanced systems that feature improved specifications and data processing algorithms.

It is worth noting that studies were conducted on the reproducibility of the results at various biomechanics laboratories. The results showed that the best reproducibility of the kinematics and kinetics data was achieved by controlling the walking speed and the installation of markers [47].

To exclude the human factor in the technique of placing markers on anatomical points using the palpation method, some researchers have proposed a device that helps to more correctly attach the markers on the patient's body and increase the reproducibility of the results [41, 48]. But, despite the fact that such devices can improve the accuracy of the results, their use in patients with cerebral palsy and other deformities of the musculoskeletal system is very limited. Therefore, one should use the atlas of anatomical landmarks to determine the centers of rotation of human joints by palpation [49].

IOR (Instituti Ortopedici Rizzoli) model

This model has found its wide application in the clinical evaluation of walking biomechanics, and its methodology for attaching the markers is well described in the literature [50]. This model is able to register the kinematics of all human body segments and calculation of the sagittal balance. The advantage of this model is the absence of clusters; therefore, EMG sensors for recording muscle activity can be freely adjusted. One can use the IOR-model with minimum system configuration (6 cameras in total), but it is recommended to use a larger number. Figure 3 (a) shows the layout of the markers. All markers of this model are used to build a static model (modeling of human body segments), and yellow markers (located in the medial part of the joints of the lower extremities) are removed during dynamic recording, as the patient can knock them down in various pathologies. IOR is a model suitable for clinical gait analysis of patient's low walking speed, which reduces the artifacts of skin movements. Such a model is not always suitable for running as it produces stronger skin movements, especially when analyzing the knee joint.

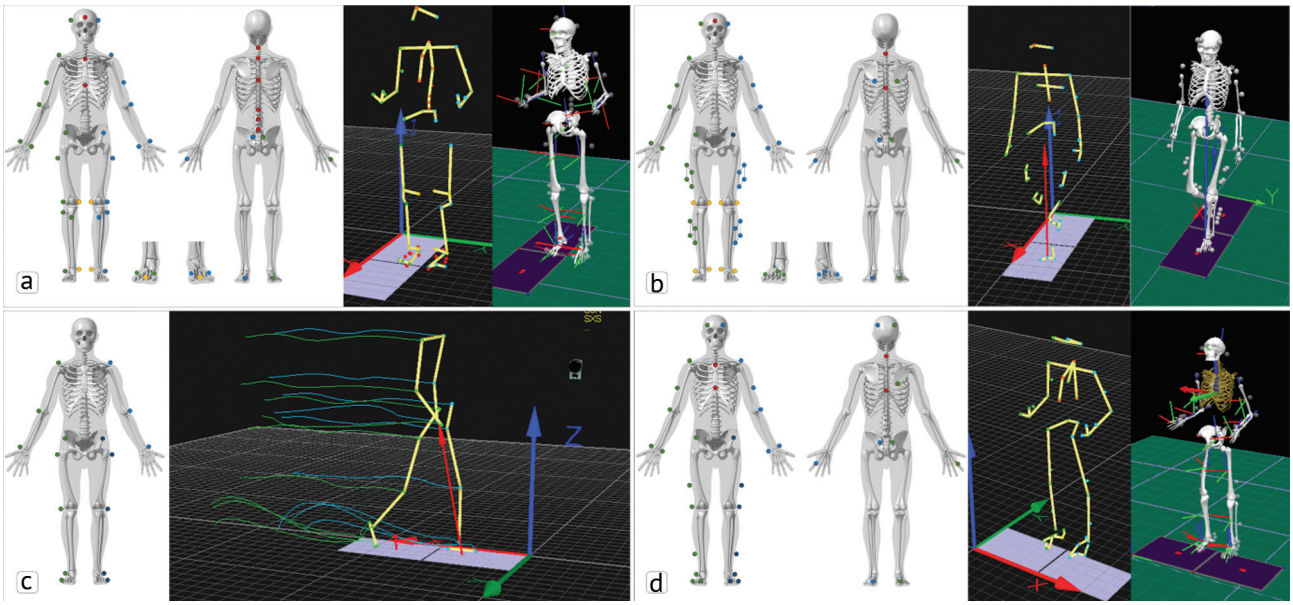

Fig. 3 Models for reconstruction of human body segments in Visual3D (C-Motion), used in the analysis of walking; yellow markers are removed during dynamic gait recording: *a* – IOR model; *b* – CAST model; *c* – standard 2D model; *d* – simplified CGM model

CAST model

The CAST (calibrated anatomical system technique) method was proposed by Cappozzo and his colleagues in 1995 [51, 52]. The method is divided into static calibration with the construction of a model of the human skeleton and the dynamic method of motion detection using marker clusters with reconstruction of a static model on them. Figure 3 (b) shows the marker pattern for static and dynamic models. To identify the human skeleton segments, markers and clusters are used, and yellow markers are removed during dynamic recording. This method has several shortcomings: four markers are mounted on a plastic plate (cluster) and attached to each segment of the leg with the help of elastic bands. On the one hand, this technique reduces skin artifacts, and, on the other hand, the patient feels discomfort by walking or can change the nature of the gait. If the cluster is not firmly seated and free movements occur, reproduction of locomotor movements of the ankle, knee and hip joint is not accurate. Sometimes it is difficult to mount EMG sensors as the area for mounting may be overlapped with the cluster. If the doctor uses a wrong technique of attaching clusters, for example, on muscles, that change their volume during motion, then additional errors may be present in the results of the examination. CAST has found its application in sports, as clusters may be firm seated and it is more difficult to detach them.

CGM (Conventional Gait Model)

This model is very limited and does not detect the centers of rotation of the joints accurately, for example, the knee (Fig. 3, d). To model the skeleton, additional dimensions of the patient's hip, knee, and ankle volumes are required to determine the center of the joints.

This method is very rarely used in clinical practice; however, with a minimum number of cameras (for example, 5) such a model allows for 3D-recording of movements.

Standard 2D model for recording in the sagittal plane

It is sufficient to use only two cameras for 2D-recording of symmetric movements of the right and left side of the human body in the sagittal plane [17]. This model is the most economical for laboratories. However, 3D analysis is the "gold" standard in clinical biomechanics, since it provides recording of motion of segments with six degrees of freedom (6DOF). In the studies conducted in 2017, a comparative analysis of 2D and 3D video-analysis methods showed a relatively satisfactory correlation of results in the sagittal plane of the lower extremities, which does not refer to the frontal one [53]. Also, the use of a standard 2D model limits the ability to analyze the kinetics of patient movements (moments, powers, foot roll over center and other parameters). The model of attaching the markers is shown in Figure 3 (c).

Other models

There are other models that were used in clinical practice in the early 2000s, such as Vaughan, Helen Hayes, and mixed ones [54–56]

Oxford Foot Model

The foot is a complex anatomical structure consisting of a set of joints that provide movement. Therefore, presenting it as a single solid segment can affect the accuracy of results. At present, there are many developments of the multi-component foot model. However, the Oxford Foot Model has found the widest application. It consists of three segments (hindfoot, midfoot, forefoot) and is able to reflect the biomechanics of movement of various sections of the foot while walking (**Fig. 4**).

The Oxford foot model has demonstrated good reproducibility in children and adults [57, 58, 59]. The modeling method is described in detail in the articles and on the C-motion Wiki website [15, 58].

It is worth emphasizing that with shoes on, the attachment of markers for modeling a multi-segment foot becomes difficult, and special shoes supplied with holes are used [60, 61] (Fig. 4). However, the full functionality of such shoes with holes is lost if we compare the biomechanics of walking in shoes without holes [62, 63]. Therefore, to improve the results, it is recommended to use tight fitting footwear to reduce the free movement of the foot inside it.

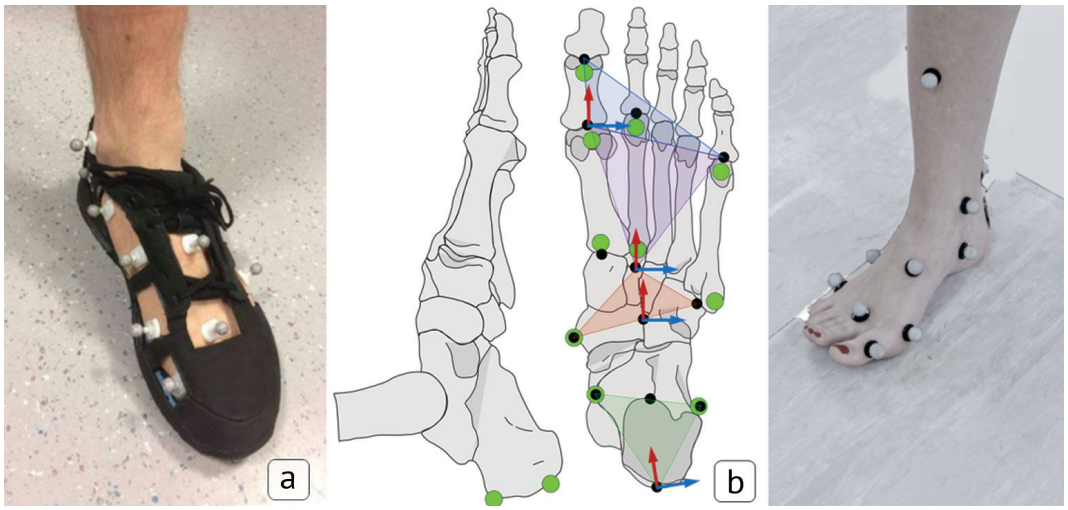

Fig. 4 Adapted shoes for modeling a multi-component foot a [60]; b "Oxford Foot" (green points show application of markers; black points are joints; the triangles represent the segments lined up with this model

CONCLUSIONS

The method of video-based analysis (clinical gait analysis) of biomechanics in clinical practice is the "gold" standard for assessing the efficiency in rehabilitation of motor functions and treatment of disorders of the musculoskeletal system.

Main recommendations for researchers were drawn up for conducting clinical gait analysis.

The basic models of adjusting markers for clinical analysis of the gait in patients with cerebral palsy are described. It is found that the IOR model is optimal for clinical analysis of the gait in a patient with a low walking speed and under minimum configuration of the system (6 cameras). The Oxford Foot Model (Oxford Foot) is highlighted as it enables a more detailed reflection of the biomechanics of movements of various foot parts during walking.

A well-thought-out working laboratory protocol, a properly chosen methodology of tests as well as equipment and an automated analysis developed allow for complete diagnosis supplied with clinical reports within 45–60 minutes. Clinical laboratories are recommended to use a system consisting of 10 to 12 cameras, two to four force platforms, and a wireless EMG system. The IOR model should be used for simulation and analysis of gait biomechanics in patients with cerebral palsy.

REFERENCES

1. Theologis T., Stebbins J. The use of gait analysis in the treatment of pediatric foot and ankle disorders. *Foot Ankle Clin.*, 2010, vol. 15, no. 2, pp. 365-382 DOI: 10.1016/j.fcl.2010.02.002.
2. Wren T.A., Gorton G.E. 3rd, Ounpuu S., Tucker C.A. Efficacy of clinical gait analysis: A systematic review. *Gait Posture*, 2011, vol. 34, no. 2, pp. 149-153. DOI: 10.1016/j.gaitpost.2011.03.027.
3. Borzikov V.V. Videoanaliz dvizhenii cheloveka v klinicheskoi praktike (obzor) [Video analysis of human movements in clinical practice (review)]. *Sovremennye Tekhnologii v Meditsine (STM J)*, 2015, vol. 7, no. 4, pp. 201-210. (in Russian)
4. Likhachev S.A., Lukashevich V.A. Videoanaliz shagovogo dvizheniia: fenomenologiia vizualnoi otsenki [Video analysis of step motion: the phenomenology of visual assessment]. *Mezhdunarodnyi Nevrologicheskii Zhurnal*, 2012, no. 2, pp. 178-182. (in Russian)
5. Smirnova I.V., Samsonova T.V. Funktsionalnaia diagnostika dvigatelnoi patologii v detskom vozraste [Functional diagnosis of motor pathology in childhood]. *Detskaia Meditsina Severo-Zapada*, 2012, vol. 3, no. 1, pp. 36-40. (in Russian)
6. Feng Y., Max L. Accuracy and precision of a custom camera-based system for 2-d and 3-d motion tracking during speech and nonspeech motor tasks. *J. Speech Lang. Hear. Res.*, 2014, vol. 57, no. 2, pp. 426-438. DOI: 10.1044/2014_JSLHR-S-13-0007.
7. Leonchuk S.S., Chibirov G.M., Popkov D.A. Korrektsiia deformatsii stopy po metodike evans u rebenka s dtsp v ramkakh odnomomentnogo mnogourovnevogo ortopedicheskogo vmeshatelstva. Sluchai iz praktiki [Foot deformity correction according to Evans technique in a child with cerebral palsy within performing the acute multilevel orthopedic intervention. A case report]. *Genij Ortopedii*, 2016, no. 3, pp. 77-83. (in Russian)
8. Lee E.H., Goh J.C., Bose K. Value of gait analysis in the assessment of surgery in cerebral palsy. *Arch. Phys. Med. Rehabil.*, 1992, vol. 73, no. 7, pp. 642-646.
9. Tugui R.D., Antonescu D. Cerebral palsy gait, clinical importance. *Maedica* (Buchar), 2013, vol. 8, no. 4, pp. 388-393.
10. Armand S., Decoulon G., Bonnefoy-Mazure A. Gait analysis in children with cerebral palsy. *EFORT Open Rev.*, 2016, vol. 1, no. 12, pp. 448-460. DOI: 10.1302/2058-5241.1.000052.
11. Gage J.R., Schwartz M.H., Koop S.E., Novachek T.F., eds. *The Identification and Treatment of Gait Problems in Cerebral Palsy*. 2nd Ed. Cambridge UK, Mac Keith Press, 2009, 660 p.
12. Schwartz M.H., Rozumalski A. The Gait Deviation Index: a new comprehensive index of gait pathology. *Gait Posture*, 2008, vol. 28, no. 3, pp. 351-357. DOI: 10.1016/j.gaitpost.2008.05.001.
13. Baker R., McGinley J.L., Schwartz M.H., Beynon S., Rozumalski A., Graham H.K., Tirosh O. The gait profile score and movement analysis profile. *Gait Posture*, 2009, vol. 30, no. 3, pp. 265-269. DOI: 10.1016/j.gaitpost.2009.05.020.
14. Beynon S., McGinley J.L., Dobson F., Baker R. Correlations of the Gait Profile Score and the Movement Analysis Profile relative to clinical judgments. *Gait Posture*, 2010, vol. 32, no. 1, pp. 129-132. DOI: 10.1016/j.gaitpost.2010.01.010.
15. Carson M.C., Harrington M.E., Thompson N., O'Connor J.J., Theologis T.N. Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis. *J. Biomech.*, 2001, vol. 34, no. 10, pp. 1299-1307.
16. Gordon D., Robertson E., Caldwell E.G., Hamill J., Kamen G., Whittlesey S.N., eds. *Research Methods in Biomechanics*. 2nd Ed. Champaign, IL, Human Kinetics, 2014, 440 p.
17. Richards J. *The Comprehensive Textbook of Clinical Biomechanics*. 2nd Ed. Elsevier, 2018, 384 p.
18. Whittle M. *An Introduction to Gait Analysis*. 4th Ed. M. Whittle, ed. Butterworth-Heinemann, 2006, 244 p.
19. Perry J., Burnfield J. *Gait Analysis: Normal and Pathological Function.* New Jersey, SLACK Incorporated, 1992.
20. Winter D.A. *Biomechanics and Motor Control of Human Movement*. 4th Ed. Wiley, 2009, 384 p.
21. Kirtley C. *Clinical Gait Analysis: Theory and Practice*. Edinburgh, New York, Elsevier, 2006, 316 p.
22. Udochkina L.A., Vorontsova O.I., Galushko T.G., Goncharova L.A., Akhmineeva A.Kh., Mazin I.G. Analiz dvizhenii v kolennom sustave v shagovom tsikle u iunoshei i muzhchin 17-25 let [The analysis of movements in the knee in the step cycle in juveniles and men of 17-25 years old]. *Kurskii Nauchno-prakticheskii Vestnik "Chelovek i Ego Zdorove"*, 2016, no. 4, pp. 94-99. (in Russian)
23. Dicharry J. Kinematics and kinetics of gait: from lab to clinic. *Clin. Sports Med.*, 2010, vol. 29, no. 3, pp. 347-364. DOI: 10.1016/j.csm.2010.03.013.
24. Richards J. *Biomechanics in Clinic and Research: An interactive teaching and learning course*. 1st Ed. Churchill Livingstone, 2008, 232 p.
25. Aksenov A. *An investigation into the relationship between rocker sole designs and alteration to lower limb kinetics, kinematics and muscle function during adult gait*. Ph.D. Thesis. Salford UK, University of Salford, Centre for Health Research School of Health Sciences, 2014. 390 p.
26. Aksenov A.Yu., Klishkovskaya T.A. Primenenie videoanaliza s tseliu opredeleniia optimalnoi konstruktsii obuvi dlia snizheniia adduktsionnogo momenta kolennogo sustava [The use of video analysis in order to determine the optimal design of the shoe to reduce the knee adduction moment]. *Ortopediia, Travmatologiia i Vosstanovitelnaia Khirurgiia Detskogo Vozrasta*, 2017, vol. 5, no. 1, pp. 45-52. (in Russian)
27. Voloshina A.S., Kuo A.D., Daley M.A., Ferris D.P. Biomechanics and energetics of walking on uneven terrain. *J. Exp. Biol.*, 2013, vol. 216, pt. 21, pp. 3963-3970. DOI: 10.1242/jeb.081711.
28. Kesler A., Leibovich G., Herman T., Gruendlinger L., Giladi N., Hausdorff J.M. Shedding light on walking in the dark: the effects of reduced lighting on the gait of older adults with a higher-level gait disorder and controls. *J. Neuroeng. Rehabil.*, 2005, vol. 2, pp. 27. DOI: 10.1186/1743-0003-2-27.

29. Kirtley C., Whittle M.W., Jefferson R.J. Influence of walking speed on gait parameters. *J. Biomed. Eng.*, 1985, vol. 7, no. 4, pp. 282-288.
30. Chen I.H., Kuo K.N., Andriacchi T.P. The influence of walking speed on mechanical joint power during gait. *Gait Posture*, 1997, vol. 6, no. 3, pp. 171-176.
31. Holden J.P., Chou G., Stanhope S.J. Changes in knee joint function over a wide range of walking speeds. *Clin. Biomech.*, 1997, vol. 12, no. 6, pp. 375-382.
32. Waters R.L., Mulroy S. The energy expenditure of normal and pathologic gait. *Gait Posture*, 1999, vol. 9, no. 3, pp. 207-231.
33. Hof A.L., Elzinga H., Gimmius W., Halbertsma J.P. Speed dependence of averaged EMG profiles in walking. *Gait Posture*, 2002, vol. 16, no. 1, pp. 78-86.
34. Den Otter A.R., Geurts A.C., Mulder T., Duysens J. Speed related changes in muscle activity from normal to very slow walking speeds. *Gait Postur*e, 2004, vol. 19, no. 3, pp. 270-278.
35. Van Hedel H.J., Tomatis L., Müller R. Modulation of leg muscle activity and gait kinematics by walking speed and bodyweight unloading. *Gait Posture*, 2006, vol. 24, no. 1, pp. 35-45.
36. Byrne C.A., O'Keeffe D.T., Donnelly A.E., Lyons G.M. Effect of walking speed changes on tibialis anterior EMG during healthy gait for FES envelope design in drop foot correction. *J. Electromyogr. Kinesiol.*, 2007, vol. 17, no. 5, pp. 605-616.
37. Chiu M.C., Wang M.J. The effect of gait speed and gender on perceived exertion, muscle activity, joint motion of lower extremity, ground reaction force and heart rate during normal walking. *Gait Posture*, 2007, vol. 25, no. 3, pp. 385-392. DOI: 10.1016/j.gaitpost.2006.05.008.
38. Stoquart G., Detrembleur C., T. Lejeune. Effect of speed on kinematic, kinetic, electromyographic and energetic reference values during treadmill walking. *Neurophysiol. Clin.*, 2008, vol. 38, no. 2, pp. 105-116. DOI: 10.1016/j.neucli.2008.02.002.
39. Chung M.J., Wang M.J. The change of gait parameters during walking at different percentage of preferred walking speed for healthy adults aged 20–60 years. *Gait Posture*, 2010, vol. 31, no. 1, pp. 131-135. DOI: 10.1016/j.gaitpost.2009.09.013.
40. Sousa A.S., Tavares J.M. Effect of gait speed on muscle activity patterns and magnitude during stance. *Motor Control.*, 2012, vol. 16, no. 4, pp. 480-492.
41. Hutchinson L., Schwartz J.B., Morton A.M., Davis I.S., Deluzio K.J., Rainbow M.J. Operator Bias Errors Are Reduced Using Standing Marker Alignment Device for Repeated Visit Studies. *J. Biomech. Eng.*, 2018, vol. 140, no. 4. DOI: 10.1115/1.4038358.
42. Manal K., McClay I., Stanhope S., Richards J., Galinat B. Comparison of surface mounted markers and attachment methods in estimating tibial rotations during walking: an in vivo study. *Gait Posture*, 2000, vol. 11, no. 1, pp. 38-45.
43. Reinschmidt C., Van den Bogert A.J., Nigg B.M., Lundberg A., Murphy N. Effect of skin movement on the analysis of skeletal knee joint motion during running. *J. Biomech.*, 1997, vol. 30, no. 7, pp. 729-732.
44. Manal K., McClay D.I., Galinat B., Stanhope S. The accuracy of estimating proximal tibial translation during natural cadence walking: bone vs. skin mounted targets. *Clin. Biomech.* (Bristol, Avon), 2003, vol. 18, no. 2, pp. 126-131.
45. Fuller J., Liu L.-J., Murphy M.C., Mann R.W. A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers. *Human Movement Science* (Elsevier), 1997, vol. 16, no. 2-3, pp. 219-242. Available at: https://doi.org/10.1016/S0167-9457(96)00053-X.
46. Wachowsky M., Dsouza S., Wirth T. Comparison of gait kinematics in children using the calibration anatomical system technique based model (CAST), Instituti Ortopedici Rizzoli (IOR) model and modified Helen Hayes (MHH) model. *Gait Posture*, 2015, vol. 42, pp. S98. DOI: 10.1016/j.gaitpost.2015.06.179.
47. Kaufman K., Miller E., Kingsbury T., Russel Esposito E., Wolf E., Wilken J., Wyatt M. Reliability of 3D gait data across multiple laboratories. *Gait Posture*, 2016, vol. 49, pp. 375-381. DOI: 10.1016/j.gaitpost.2016.07.075.
48. Noehren B., Manal K., Davis I. Improving between-day kinematic reliability using a marker placement device. *J. Orthop. Res.*, 2010, vol. 28, no. 11, pp. 1405-1410. DOI: 10.1002/jor.21172.
49. Van Sint Jan S. *Color Atlas of Skeletal Landmark Definitions. Guidelines for Reproducible Manual and Virtual Palpations*. 1st Ed. Edinburgh, Churchill Livingstone, 2007. 208 p.
50. Leardini A., Sawacha Z., Paolini G., Ingrosso S., Nativo R., Benedetti M.G. A new anatomically based protocol for gait analysis in children. *Gait Posture*, 2007, vol. 26, no. 4, pp. 560-571. DOI: 10.1016/j.gaitpost.2006.12.018.
51. Cappozzo A., Catani F., Croce U.D., Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin. Biomech.* (Bristol, Avon), 1995, vol. 10, no. 4, pp. 171-178.
52. Cappello A., Cappozzo A., La Palombara P.F., Lucchettin L., Leardini A. Multiple anatomical landmark calibration for optimal bone pose estimation. *Human Movement Science* (Elsevier), 1997, vol. 16, no. 2-3, pp. 259-274.
53. Schurr S.A., Marshall A.N., Resch J.E., Saliba S.A. Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *Int. J. Sports Phys. Ther.*, 2017, vol. 12, no. 2, pp. 163-172.
54. Collins T.D., Ghoussayni S.N., Ewins D.J., Kent J.A. A six degrees-of-freedom marker set for gait analysis: repeatability and comparison with a modified Helen Hayes set. *Gait Posture*, 2009, vol. 30, no. 2, pp. 173-180. DOI: 10.1016/j.gaitpost.2009.04.004.
55. Tabakin D. *A comparison of 3D gait models based on the Helen Hayes Hospital marker set*. Thesis. University of Cape Town, Department of Human Biology, 2000. Available at: http://hdl.handle.net/11427/3206.
56. Davis R.B. III, Ounpuu S., Tyburski D., Gage J.R. A gait analysis data collection and reduction technique. *Human Movement Science*, 1991, vol. 10, no. 5, pp. 575-587. DOI: 10.1016/0167-9457(91)90046-z.
57. Curtis D.J., Bencke J., Stebbins J.A., Stansfield B. Intra-rater repeatability of the Oxford foot model in healthy children in different stages of the foot roll over process during gait. *Gait Posture*, 2009, vol. 30, no. 1, pp. 118-121. DOI: 10.1016/j.gaitpost.2009.02.013.

58. Stebbins J., Harrington M., Thompson N., Zavatsky A., Theologis T. Repeatability of a model for measuring multi-segment foot kinematics in children. *Gait Posture*, 2006, vol. 23, no. 4, pp. 401-410. DOI: 10.1016/j.gaitpost.2005.03.002.
59. McCahill J., Stebbins J., Koning B., Harlaar J., Theologis T. Repeatability of the Oxford Foot Model in children with foot deformity. *Gait Posture*, 2018, vol. 61, pp. 86-89. DOI: 10.1016/j.gaitpost.2017.12.023.
60. Eerdekens M., Staes F., Pilkington T., Deschamps K. A novel magnet based 3D printed marker wand as basis for repeated in-shoe multi segment foot analysis: a proof of concept. *J. Foot Ankle Res.*, 2017, vol. 10, pp. 38. DOI: 10.1186/s13047-017-0220-7.
61. Halstead J., Keenan A.M., Chapman G.J., Redmond A.C. The feasibility of a modified shoe for multi-segment foot motion analysis: a preliminary study. *J. Foot Ankle Res.*, 2016, vol. 9, pp. 7. DOI: 10.1186/s13047-016-0138-5.
62. Sinlair J., Greenhalgh A., Taylor P.J., Edmundson C.J., Brooks D., Hobbs S.J. Differences in tibiocalcaneal kinematics measured with skin- and shoe-mounted markers. *Human Movement*, 2013, vol. 14, no. 1, pp. 64-69.
63. Aksenov A.Yu., Matveeva V.N., Klishkovskaya T.A. Sravnenie dvukh metodov registratsii kinematiki i kinetiki golenostopnogo sustava pri ispolzovanii videoanaliza [The comparison of two methods of the ankle kinematics and kinetics registration using video analysis]. *Dostizheniia Nauki i Obrazovaniia*, 2016, no. 7 (8), pp. 10-16. (in Russian)

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