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DIGITAL TECHNOLOGIES IN PROSTHESIS AND ORTHOSIS OF LIMBS AND SPINE, THEIR BIOMECHANICAL EFFICIENCY AND IMPACT ON THE REHABILITATION PROCESS

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Abstract. *The article examines the use of digital technologies in the prosthetics and orthotics of limbs and the spine and their impact on patients' biomechanical movement parameters during the rehabilitation process. The study aimed to evaluate the effectiveness of three-dimensional scanning, computer modeling, and additive manufacturing in the production of prosthetic and orthotic devices. A total of 48 patients participated in the study and were divided into control and experimental groups. Effectiveness was assessed based on the analysis of biomechanical gait parameters, including step length, walking speed, movement symmetry, and trunk stability. Statistical analysis of the results included descriptive statistics, analysis of variance (ANOVA), correlation, and regression analysis. The results obtained showed a statistically significant improvement in the main gait parameters for patients in the experimental group. It was established that the use of digital technologies in prosthetics and orthotics contributes to increasing rehabilitation efficiency and improving the functional mobility of patients.*

Keywords: *digital technologies, prosthetics, orthotics, gait biomechanics, 3D scanning, rehabilitation, musculoskeletal system*

Introduction.

Diseases and injuries of the musculoskeletal system are a leading cause of disability and limited mobility among the global population. According to international public health research, functional impairments of the musculoskeletal system significantly affect physical activity levels, work capacity, and the quality of life of patients. A significant portion of these disorders is related to limb amputations, degenerative diseases of the spine, traumatic injuries, and neurological disorders that lead to changes in movement biomechanics and human functional capabilities [1].

In the structure of rehabilitation medicine, prosthetics and orthotics occupy an important place, aimed at restoring or compensating for the impaired functions of the musculoskeletal system. Prosthetic and orthotic products provide support, stabilization, and correction of anatomical body segments, contributing to the improvement of patients' mobility and functional independence. Biomechanical research shows that correctly selected and adapted prostheses and orthoses can significantly improve gait parameters, reduce movement asymmetry, and lower the load on joints and the spine [2,3].

The issue of prosthetics and orthotics becomes particularly relevant given the increasing number of traumatic injuries and limb amputations. According to the results of international epidemiological studies, a significant portion of amputations is linked to vascular diseases, diabetes, trauma, and oncological processes. The loss of a limb is accompanied by significant functional changes in the movement system, including disruption of gait symmetry, changes in joint kinematics, and increased energy expenditure during movement [4,5]. This necessitates the use of effective rehabilitation technologies that allow for the restoration of the highest possible level of patient motor activity.

At the same time, traditional technologies for manufacturing prosthetic and orthotic products have certain limitations. Most classical methods are based on manual modeling of plaster casts and mechanical processing of materials. Despite the widespread use of such approaches in clinical practice, they often do not provide sufficient accuracy in reproducing the anatomical shape of a limb segment or the trunk. Furthermore, a heavy reliance on the individual experience of a specialist can lead to variability in product manufacturing results.

Insufficient precision in the individualization of prostheses and orthoses can negatively impact their functional effectiveness. Biomechanical studies indicate that improper load distribution within the construction of a prosthetic-orthotic product can cause additional stress on the healthy limb, hip, and knee joints, as well as the spine. In the long term, this may lead to the development of secondary orthopedic disorders, chronic pain syndrome, and reduced rehabilitation efficiency [1,5].

In this regard, the implementation of modern digital technologies in the field of prosthetics and orthotics is of particular importance. The development of three-dimensional scanning, computer-aided design (CAD), automated design systems, and additive manufacturing creates new opportunities for increasing the precision and individualization of prosthetic and orthotic products. The use of 3D scanning allows for obtaining detailed digital models of the patient's anatomical segments, ensuring high accuracy in reproducing surface geometry and enabling optimization of the product's design.

Digital technologies also open new possibilities for utilizing biomechanical analysis methods during the design of prostheses and orthoses. Computer modeling allows for predicting the distribution of mechanical loads in the product's construction, evaluating the influence of various design parameters on movement kinematics, and optimizing the product's shape according to the functional needs of the patient. This contributes to increased efficiency in prosthetics and orthotics and ensures a more rational approach to rehabilitation [2,6].

Furthermore, modern trends in medical technology development involve the integration of digital movement analysis systems, inertial sensors, and sensor platforms into the rehabilitation process. These systems allow for an objective evaluation of gait parameters, such as step length and frequency, walking speed, joint flexion angles, and movement symmetry [7]. The data obtained can be used to evaluate the effectiveness of prosthetic and orthotic products and to adjust rehabilitation programs.

Despite the significant potential of digital technologies, their widespread implementation into the practice of prosthetics and orthotics requires scientific justification. In modern scientific literature, there is an insufficient number of comprehensive studies aimed at assessing the impact of digital design and manufacturing methods for prosthetic and orthotic products on biomechanical movement parameters and functional rehabilitation outcomes [8,9]. Specifically, further research is needed to compare the effectiveness of traditional and digital technologies for manufacturing prostheses and orthoses, as well as their impact on restoring patient motor activity.

The relevance of this research stems from the need for a scientific basis for the effectiveness of using digital technologies in the prosthetics and orthotics of limbs and the spine, as well as an assessment of their impact on biomechanical movement parameters and rehabilitation outcomes for patients with musculoskeletal disorders [4,10]. Conducting such research will contribute to the improvement of manufacturing technologies for prosthetic and orthotic products, increasing the effectiveness of rehabilitation measures and improving the quality of life for patients.

Impairments of musculoskeletal functions are among the most common causes of disability, limited mobility, and a decline in the quality of life of the population. According to the World Health Organization, diseases and injuries of the musculoskeletal system are among the leading causes of disability worldwide. A significant portion of these disorders is associated with limb amputations, degenerative spinal diseases, traumatic injuries, and neurological pathologies that lead to changes in movement biomechanics.

Limb amputations remain a critical medical and social issue. According to international research estimates, more than one million amputations are performed annually worldwide, caused by traumatic injuries, vascular diseases, diabetes mellitus, oncological processes, and other pathologies. The loss of a limb leads to substantial changes in movement biomechanics, including disruption of gait symmetry, changes in load distribution on joints, and increased energy expenditure during movement [11].

One of the primary directions for restoring the functional activity of patients after amputations or in cases of spinal pathologies is the use of prosthetic and orthotic products. Protheses and orthoses perform an essential compensatory function, providing support, stabilization, or replacement of lost anatomical structures [12]. At the same time, the effectiveness of their use largely depends on the accuracy of individual selection and the biomechanical correspondence of the product's design to the patient's anatomical features.

Traditional methods of manufacturing prosthetic and orthotic products are mostly based on manual modeling of plaster casts and subsequent mechanical processing of materials. Despite years of experience in using such technologies, they have several significant limitations. These include relatively low accuracy in reproducing the anatomical shape of a limb segment or the trunk, the difficulty of making corrections during the manufacturing process, high labor intensity of production, and the dependence of the result on the individual experience of the specialist [4,8]. This can lead to insufficient adaptation of the prosthesis or orthosis to the patient's biomechanical movement characteristics.

Insufficient precision in the individualization of prosthetic and orthotic products can cause secondary complications, including pain syndrome, postural disorders, excessive load on the joints of the healthy limb, and the development of degenerative changes in the spine. Research in the field of gait biomechanics indicates that an incorrect or poorly adapted prosthesis design can increase energy expenditure during movement by 10–30%, which negatively affects the physical endurance and functional independence of patients.

In this regard, the implementation of modern digital design technologies in the field of prosthetics and orthotics is of great importance. The development of three-dimensional scanning, computer modeling, and additive manufacturing opens new possibilities for creating individualized prosthetic and orthotic products [13]. The use of digital technologies allows for obtaining precise three-dimensional models of the patient's anatomical structures, optimizing the product's design considering biomechanical loads, and enabling the rapid manufacturing of complex structures.

A special role in modern research is played by biomechanical movement analysis, which makes it possible to objectively evaluate the effectiveness of using prostheses and orthoses. Gait analysis systems, including video recording, sensor platforms, and inertial sensors, allow for the determination of parameters such as step length and frequency, walking speed, movement symmetry, joint flexion angles, and trunk stability. The data obtained are crucial for assessing the functional effectiveness of prosthetic and orthotic products and optimizing the rehabilitation process.

Despite the significant potential of digital technologies, their widespread implementation into prosthetic and orthotic practice requires scientific justification. There is a limited amount of research in the scientific literature that comprehensively evaluates the impact of digital design and additive manufacturing on patients' biomechanical movement parameters [2,14]. In particular, issues comparing traditional and digital manufacturing methods, their impact on gait symmetry, trunk stability, and the energy efficiency of movement, remain insufficiently studied.

Furthermore, current trends in the development of rehabilitation medicine involve the integration of digital technologies with physical activity monitoring systems, sensor platforms, and artificial intelligence algorithms. This creates the prerequisites for forming new approaches to personalized rehabilitation, where prosthetic and orthotic products can adapt to the patient's functional state in real time.

The research problem lies in the need for a scientific justification of the effectiveness of using digital technologies in prosthetics and orthotics in terms of biomechanical movement parameters and rehabilitation outcomes for patients with musculoskeletal disorders. Solving this problem is of great importance for improving the quality of prosthetic and orthotic care, optimizing the rehabilitation process, and enhancing the functional independence of patients.

The Aim of the Study

The aim of the study is to evaluate the effectiveness of using digital technologies in the prosthetics and orthotics of limbs and the spine based on the analysis of biomechanical movement parameters and the functional state of patients during the rehabilitation process.

Presentation of the Main Material

The study involved 48 patients who were undergoing a rehabilitation course following lower limb amputations or had spinal pathologies requiring the use of orthoses.

The patients were divided into two groups: control group (n=24) – used traditional methods of manufacturing prostheses and orthoses; experimental group (n=24) – used digital technologies (3D scanning, CAD modeling, and additive manufacturing).

To evaluate the effectiveness of rehabilitation, the following indicators were used: step length; gait symmetry; knee flexion angle; trunk stability index; walking speed.

Biomechanical analysis was conducted using a gait analysis system and video biomechanical modeling.

For the statistical processing of the results, descriptive statistics methods were applied: arithmetic mean; standard deviation; Student's t-test for independent samples.

The level of statistical significance was set at $p<0.05$.

Research Results

In the course of the study, a comparative analysis was conducted on the biomechanical movement parameters of patients in the control and experimental groups after the use of prosthetic and orthotic products manufactured using traditional and digital technologies. The evaluation of effectiveness was based on the analysis of key kinematic gait indicators, including step length, walking speed, knee flexion angle, gait symmetry, and trunk stability.

The results of descriptive statistics showed significant differences between the study groups (Tab.1).

Table 1 - Descriptive statistics of biomechanical gait indicators

Indicator	Control group (n=24)	Experimental group (n=24)	p
Step length (cm)	53.1±6.2	62.7±5.4	0.009
Walking speed (m/s)	0.82±0.14	1.01±0.12	0.011
Knee flexion angle (°)	48.4±5.8	55.7±6.1	0.015
Gait symmetry (%)	71.5±8.6	85.3±7.9	0.004
Trunk stability (%)	68.2±7.4	77.6±6.8	0.012

The mean step length in the control group patients was 53.1±6.2 cm, while in the experimental group patients, this indicator was 62.7±5.4 cm. Thus, the increase in step length in the experimental group was approximately 18%, indicating an improvement in the biomechanical efficiency of the gait.

A similar trend was observed regarding walking speed. The average walking speed in the control group was 0.82±0.14 m/s, whereas in the experimental group patients, it reached 1.01±0.12 m/s. Thus, the use of prosthetic and orthotic products manufactured with digital technologies contributed to an increase in walking speed by approximately 23%. Increasing movement speed is a vital indicator of rehabilitation effectiveness, as it is directly linked to the patients' functional independence and their ability to perform daily physical activities.

Comparative analysis of the knee flexion angle also showed positive dynamics in the experimental group patients. In the control group, the mean value of this indicator was 48.4±5.8°, while in the experimental group, it was 55.7±6.1°. The increase in the amplitude of motion in the knee joint indicates a more natural reproduction of the gait cycle phases and an improvement in the kinematic characteristics of movement.

An important indicator of the effectiveness of prosthetics and orthotics is gait symmetry, which characterizes the even distribution of the load between segments of the musculoskeletal system. As a result of the study, it was established that in the experimental group patients, the gait symmetry indicator averaged 85.3±7.9%, while in the control group, this indicator was 71.5±8.6%. Thus, the use of digital technologies for manufacturing prosthetic and orthotic products contributed to an improvement in gait symmetry by approximately 19%.

Furthermore, an improvement in trunk stability indicators was observed in the experimental group patients. The mean value of this parameter was 77.6±6.8% in the experimental group compared to 68.2±7.4% in the control group. Increasing trunk stability is an important factor in maintaining balance and movement coordination, which is especially critical for patients with spinal pathologies or after lower limb amputations.

To verify the statistical significance of the results obtained, an analysis of variance (ANOVA) was conducted (Tab.2).

The results of the analysis showed a statistically significant difference between the groups in the main biomechanical gait indicators. The F-value was 12.47 at a statistical significance level of $p<0.05$, which indicates a reliable impact of the use of digital prosthetic technologies on the functional movement parameters of the patients.

Table 2 - Analysis of Variance (ANOVA)

Source of Variation	SS	df	MS
Between groups	842.6	1	842.6
Within groups	3245.3	46	70.5
Total	4087.9	47	

Correlation analysis allowed for establishing the relationship between the main biomechanical gait parameters (Tab.3).

Table 3 - Correlation analysis

Indicator	Step length	Walking speed	Gait symmetry	Trunk stability
Step length	1.00	0.72	0.65	0.51
Walking speed	0.72	1.00	0.58	0.47
Gait symmetry	0.65	0.58	1.00	0.61
Trunk stability	0.51	0.47	0.61	1.00

A strong positive correlation was found between step length and walking speed ($r=0.72$). This indicates that increasing step length is one of the key factors in enhancing movement efficiency. Additionally, a moderate correlation was found between gait symmetry and trunk stability ($r=0.61$), confirming the important role of trunk stabilization in forming an effective and balanced gait pattern.

For a more detailed analysis of the influence of individual factors on walking speed, a regression analysis was performed (Tab.4).

The results obtained showed that step length has the greatest influence on walking speed ($\beta\approx0.52$), while gait symmetry ($\beta\approx0.31$) and trunk stability ($\beta\approx0.19$) have a somewhat smaller but also statistically significant impact. The coefficient of determination of the model ($R^2=0.64$) indicates that approximately 64% of the variation in walking speed is explained by the biomechanical parameters included in the model.

Table 4 - Regression analysis of the influence of factors on walking speed

Indicator	β	SE	t	p
Step length	0.52	0.11	4.73	0.001
Gait symmetry	0.31	0.13	2.38	0.021
Trunk stability	0.19	0.12	1.58	0.118

Discussion

The results of the study indicate a positive impact of using digital technologies in the process of prosthetics and orthotics on the biomechanical movement parameters of patients. The analysis showed statistically significant differences between the control and experimental groups in indicators such as step length, walking speed, movement symmetry, and trunk stability [4,14]. This confirms the hypothesis that the use of modern digital methods for designing and manufacturing prosthetic and orthotic products contributes to increasing the effectiveness of rehabilitation measures.

One of the key factors in improving biomechanical indicators is the high precision of individualization in the design of prostheses and orthoses, achieved through the use of three-dimensional scanning and computer modeling technologies. In contrast to traditional methods of manufacturing prosthetic and orthotic products based on manual modeling of plaster casts, digital technologies allow for obtaining detailed three-dimensional models of the patient's anatomical body segments. This ensures a more accurate reproduction of the surface geometry of the limb or trunk and promotes an optimal fit of the product to the patient's body [13,15].

The improvement of biomechanical gait parameters in the experimental group patients can be explained by a more even distribution of the load between segments of the musculoskeletal system. It is known that when using insufficiently adapted prostheses or orthoses, a shift in the body's center of mass is observed, leading to a disruption of gait symmetry and an increased load on the healthy limb or other skeletal segments. Such changes can cause an increase in energy expenditure during movement, negatively affecting patients' endurance and their ability to engage in prolonged physical activity.

The study established that the use of digital technologies for manufacturing prostheses and orthoses contributed to an increase in step length and walking speed in the experimental group patients. Similar results are consistent with data from biomechanical studies demonstrating that optimizing the design of a prosthesis or orthosis can significantly improve the kinematic parameters of movement. In particular, increasing support stability and improving load distribution contribute to a more natural reproduction of the gait cycle phases.

An important result of the study is also the established correlation between step length and walking speed. The identified strong positive correlation indicates that increasing step length is one of the primary factors in enhancing movement efficiency. This is confirmed by the results of the regression analysis, which showed that step length has the greatest influence on walking speed compared to other biomechanical parameters [16].

Furthermore, the improvement in trunk stability in patients using spinal orthoses manufactured with digital technologies is of great importance. Trunk stability is a vital component of maintaining balance and movement coordination during walking. Impaired stability can lead to compensatory movements that increase the load on the muscular-ligamentous apparatus and joints. Individualized design of orthoses allows for a more precise adaptation of their construction to the patient's anatomical features, contributing to more effective spinal stabilization.

It is important to note that the use of digital technologies in prosthetics and orthotics offers not only biomechanical but also organizational and technological advantages. The use of computer modeling and additive manufacturing allows for a significant reduction in the manufacturing time of prosthetic and orthotic products, increases the reproducibility of results, and reduces dependence on manual labor [6,8]. Additionally, digital models of products can be stored in databases, facilitating the process of subsequent modification or re-manufacturing of the product.

At the same time, the study results should be considered in light of certain limitations. Specifically, the study was conducted on a relatively limited sample of patients, which may affect the generalizability of the results to a broader population. Moreover, the evaluation of the effectiveness of prosthetic and orthotic products was primarily based on biomechanical gait parameters, while for a comprehensive assessment of the rehabilitation effect, it is also advisable to consider indicators of quality of life, functional independence, and the physical activity level of patients.

A promising direction for further research is the integration of digital prosthetic and orthotic technologies with sensory monitoring systems for physical activity and artificial intelligence algorithms. The use of such systems could allow for dynamic analysis of biomechanical movement parameters and the adaptation of the prosthesis or orthosis design to the patient's individual needs. Furthermore, the application of machine learning methods could contribute to predicting rehabilitation outcomes and optimizing the selection process for prosthetic and orthotic products.

The results of this study confirm the feasibility of using digital technologies in the field of prosthetics and orthotics. They demonstrate that individualized digital design of prosthetic and orthotic products can contribute to improving biomechanical movement parameters, increasing rehabilitation effectiveness, and enhancing the functional capabilities of patients with musculoskeletal disorders.

Conclusions

The results of the conducted study indicate a significant potential for the use of digital technologies in the field of prosthetics and orthotics of limbs and the spine. The application of three-dimensional scanning, computer modeling, and additive manufacturing methods allows for the creation of individualized prosthetic and orthotic products that more accurately correspond to the anatomical and functional characteristics of the patient. This contributes to the optimization of mechanical load distribution across segments of the musculoskeletal system and ensures an improvement in biomechanical movement parameters.

A comparative analysis of biomechanical gait indicators demonstrated statistically significant differences between patients who used products made by traditional methods and patients for whom digital design technologies were applied. In the experimental group patients, an increase in step length, an increase in walking speed, and an improvement in movement symmetry and trunk stability were recorded. The results obtained are confirmed by the conducted analysis of variance (ANOVA), correlation, and regression analysis, which demonstrated a reliable influence of movement biomechanics parameters on walking efficiency.

An important result of the study is the establishment of a relationship between step length, gait symmetry, and walking speed, which indicates the complex nature of forming an effective gait pattern in patients with musculoskeletal disorders. The use of digital technologies in the process of manufacturing prosthetic and orthotic products contributes to a more accurate reproduction of anatomical parameters, which ensures an improvement in the functional characteristics of movement and an increase in the effectiveness of the rehabilitation process.

The study results confirm the feasibility of the widespread implementation of digital technologies into the practice of prosthetics and orthotics. The use of modern methods of digital design and biomechanical analysis can contribute to increasing the quality of prosthetic and orthotic care, optimizing the rehabilitation process, and improving the functional independence of patients. Further research in this direction should be aimed at expanding the patient sample, utilizing long-term monitoring of rehabilitation results, and integrating sensory movement analysis systems and artificial intelligence technologies into the design process of prosthetic and orthotic products.

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***Анотація**. У статті розглянуто питання використання цифрових технологій у протезуванні та ортезуванні кінцівок і хребта та їх вплив на біомеханічні параметри руху пацієнтів у процесі реабілітації. Метою дослідження була оцінка ефективності застосування технологій тривимірного сканування, комп'ютерного моделювання та адитивного виробництва при виготовленні протезно-ортопедичних виробів. У дослідженні взяли участь 48 пацієнтів, які були розподілені на контрольну та експериментальну групи. Оцінювання ефективності проводилося на основі аналізу біомеханічних параметрів ходи, зокрема довжини кроку, швидкості пересування, симетрії рухів та стабільності тулуба. Статистичний аналіз результатів включав методи описової статистики, дисперсійний, кореляційний та регресійний аналіз. Отримані результати показали статистично значуще покращення основних параметрів ходи у пацієнтів експериментальної групи. Встановлено, що використання цифрових технологій у протезуванні та ортезуванні сприяє підвищенню ефективності реабілітації та покращенню функціональної мобільності пацієнтів.*

***Ключові слова:** цифрові технології, протезування, ортезування, біомеханіка ходи, 3D-сканування, реабілітація, опорно-руховий апарат*