

Communication

Biomechanics of Ascending and Descending Stairs in a Patient with Transfemoral Amputation and Neural Sensory Feedback: A Case Report

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Citation: Bubanj, S.; Radenković, M.; Stanković, D.; Petković, E.; Lilić, A.; Bojić, I.; Aksović, N.; Dobrescu, T.; Bjelica, B.; Ćuk, I.; et al. Biomechanics of Ascending and Descending Stairs in a Patient with Transfemoral Amputation and Neural Sensory Feedback: A Case Report. *Symmetry* **2023**, *15*, 1443. <https://doi.org/10.3390/sym15071443>

Academic Editor: Luca Paolo Ardigo

Received: 24 May 2023

Revised: 27 June 2023

Accepted: 5 July 2023

Published: 19 July 2023



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Abstract: (1) Background: Asymmetry in gait could pose a problem for patients with transfemoral amputation, due to a higher risk for secondary comorbidities. Gait analysis during ascending and descending stairs (20 stair ascends and descends) was conducted in a patient with a unilateral transfemoral amputation and integrated neural sensory feedback (NSFB), with the aim to compare biomechanical parameters between the healthy and the prosthetic leg in conditions with and without NSFB. (2) Methods: Transversal-type research was conducted at the beginning of the patient’s rehabilitation and without prior gait training in conditions with NSFB. Complete study included several months of different gait testing with and without the NSFB. Data analyzed in this study are just a small portion of the overall dataset (only one subject, one recording session, reduced amount of trials in one condition), used for showing the validity of the proposed methodology for gait analysis and proving proof of concept. The analyzed parameters included stance, time, and speed of ascending and descending stairs in conditions with and without NSFB, measured for both legs. The data were processed using statistical software (SPSS Statistics version 24), with descriptive statistics and paired-sample *t*-tests to determine differences in gait parameters between the healthy and the prosthetic leg. (3) Results: The results revealed statistically significant differences ($p = 0.00$) in all three examined parameters (stance, time, and speed) between conditions with and without NSFB. (4) Conclusions: Gait stance, time, and the speed of ascending and descending stairs can be controlled and tailored in real time using NSFB.

Keywords: gait analysis; kinematics; stairs; differences; above-knee prosthesis; bionic leg

1. Introduction

Above-the-knee amputations have been proven to have a detrimental impact on patients' movement and quality of life due to various factors, such as vascular diseases [1], diabetes [2], or injuries [3]. These are accompanied by an increased rate of mortality [4], morbidity [5], and the appearance of secondary comorbidities, such as chronic lumbar syndrome, osteoarthritis, osteoporosis, and phantom limb pain [6–9].

Gait impairment resulting from amputation has been objectively documented across various domains, including spatiotemporal and biomechanical parameters [10,11], as well as bioenergetics parameters. Individuals with transfemoral amputation, particularly those with dysvascular morbidity as the underlying cause, walk slower by 40% than normal, consume 2.5 times more energy [12], have increased oxygen consumption by about 20% compared to a healthy person [13], and face limitations in walking longer distances outdoors [14].

The gait pattern of individuals with transfemoral amputation is characterized by a shortened stance phase and a prolonged swing phase on the prosthetic side [15]. They may also exhibit lateral bending of the trunk toward the prosthetic side due to weak hip abductors or reduced balance caused by instability of the prosthetic socket. Additionally, these individuals may push off with the healthy leg to ensure a safe passage through the swing phase without the prosthetic leg contacting the ground. Abnormalities in lateral trunk flexion and push-off forces are potential factors contributing to the development of the aforementioned chronic overuse conditions [16]. Research findings [17] confirm the presence of asymmetry in the gait of individuals with transfemoral amputation in terms of time parameters.

Investigating asymmetry in patients with transfemoral amputation is vital for advancing the knowledge in this field [18]. Asymmetry plays a significant role in determining normal and pathological gait [19]. According to Tura et al. [20], symmetry, which reflects the similarity of left and right steps, and regularity, which indicates the similarity of successive steps on the same side, are two essential aspects of gait analysis. Many individuals with transfemoral amputation exhibit an asymmetric gait in terms of both the symmetry of the gait between the left and right sides and the regularity of successive steps.

For these reasons, restoring and preserving symmetrical gait is one of the main objectives in the rehabilitation of individuals with lower limb amputation [21]. To achieve this, it is vital to conduct an adequate biomechanical gait analysis [22]. Asymmetries identified in the abnormal gait kinematics of individuals with transfemoral amputation result from a lack of NSFB and further act on the increased values of bioenergetic parameters. Bionic devices transferring motor and sensory information bidirectionally between the prosthesis and the user should be leveraged to create a new generation of high-performance bionic limbs [23], promoting health impact, safety, efficacy, and cost-effectiveness, which are important for public healthcare systems. Current high costs and global regulations impede widespread adoption, limiting approval and accessibility to personalized devices for end users [24].

Despite progress in developing lower limb prostheses, the potential benefits of returning NSFB from such devices to transfemoral amputees have not been explored enough [25]. Therefore, the aim of this research is to determine whether there is a difference in the time and speed of ascending and descending stairs between the healthy and the prosthetic leg of a patient with transfemoral amputation in conditions with and without NSFB.

2. Materials and Methods

2.1. Sample of Respondents

Following the set aim of the research, a case analysis of the respondent/volunteer S.P., with a body mass of 69.1 kg and a body height of 174 cm, with transfemoral amputation of the right leg after an accidental traumatic event, who voluntarily underwent surgical implantation of four intraneural stimulation electrodes in the remaining tibial nerve for more than 90 days, was performed. Electrodes were used to stimulate tactile and movement

2.4. Testing Procedure and Instrumentation

The stairs consisted of six steps and a platform at the top of the sixth stair, with enough room for the subject to turn (Figure 1).

People with transfemoral amputation face challenges when ascending stairs, due to limited range of motion in the hip joint and weakened knee extensors in the amputated leg. Their reduced ability to climb stairs is primarily caused by the inability to generate force in the knee joint, leading many individuals to use step-by-step techniques and skip steps while ascending.

The respondent was tasked with ascending and descending the stairs by stepping on each step without skipping, making one cycle (Figure 2). The respondent used a self-selected gait speed and was asked to finish each cycle within the time frame of 30 s.

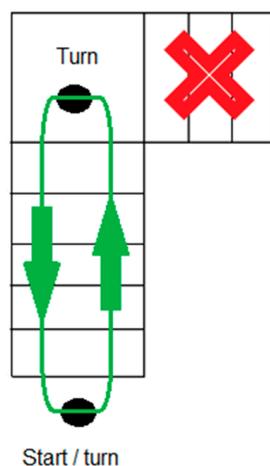


Figure 2. Gait pattern of the test protocol consisting of 20 cycles of ascending and descending stairs.

The research included 20 cycles each in conditions with and without NSFB, recorded with a digital camera operating at 100 frames per second, placed in the sagittal plane to the respondent and the stairs. The video was further analyzed using the appropriate two-dimensional (2D) marker placement model [28] and Kinovea software for motion analysis to obtain the necessary data. The Kinovea system released under the GPLv2 license, developed in 2009 through a collaborative effort involving researchers, athletes, coaches, and programmers worldwide, in a non-profit capacity [29], is proven to be valid and reliable for human movement modeling [29,30]. Transversal-type research was conducted at the beginning of the patient's rehabilitation and without prior gait training in conditions with NSFB at the Special Hospital for Rehabilitation and Orthopedic Prosthetics Rudo Belgrade.

Complete study included several months of different gait testing with and without the NSFB. Data analyzed in this study are just a small portion of the overall dataset (only one subject, one recording session, reduced amount of trials in one condition), used for showing the validity of the proposed methodology for gait analysis and proving proof of concept.

2.5. Data Processing Method

The Kinovea software used for motion analysis allowed us to acquire, process, and trim video signals to obtain the necessary data:

- Signal acquisition: We imported into Kinovea software a recorded footage of 20 gait cycles from the camera and extracted relevant signals from the recorded motion using frame-by-frame analysis of the video.
- Signal processing: Once the video was imported into Kinovea software, we performed signal processing. This included extracting specific points with markers from the video frames to track the ascending and descending of stairs. We used a combination of automatic and manual tracking tools to track the movement of selected body parts (foot, ankle joint, knee joint, hip joint, wrist joint, elbow joint, shoulder joint, head)

throughout the video sequence and to calculate the position and speed of the tracked points over time. The entire process of both automatic and manual tracking was enabled by placing reflective markers on the specified anatomical landmarks of the participant's body. After entering the appropriate scale and tracking, Kinovea software automatically calculated the values of the parameters of interest in our case study.

- Signal trimming: Where necessary, signals were trimmed to focus on specific segments of the motion. This trimming process helped us in isolating specific movements and time intervals for further analysis.

By using these features of Kinovea software, we obtained the necessary data for further analysis and interpretation.

2.6. Statistical Analysis

The data obtained were statistically processed using software for statistical data processing SPSS Statistics version 24 (IBM, Armonk, NY, USA). Descriptive statistics, including the mean, standard deviation, and standard error, were calculated before conducting any statistical tests. Since we analyzed the gait parameters of a single participant under two different conditions, paired-sample *t*-tests were performed to assess the disparities in performance with and without NSFB, as well as the discrepancies in performance between the healthy and the prosthetic leg in both conditions (with and without NSFB) [31]. The normality of the data was confirmed using the Kolmogorov–Smirnov test prior to conducting the analysis. The level of statistical significance was set at $p < 0.05$.

3. Results

Basic descriptive parameters of the stance phase and the time and speed of ascending and descending stairs in conditions with (_NSFB) and without neural sensory feedback are presented in Tables 1 and 2, respectively.

Table 1. Descriptive statistics of the stance phase.

		Condition		Ascending Stairs			Descending Stairs		
		N	NSFB	Mean	SD	SE	Mean	SD	SE
Healthy leg	STANCE (s)	20	With	3.783	0.398	0.089	3.686	0.288	0.064
			Without	4.140	0.316	0.070	3.886	0.275	0.061
With			2.990	0.288	0.060	2.988	0.260	0.058	
Without			3.086	0.360	0.080	3.413	0.301	0.067	

Note: NSFB—neural sensory feedback activated (condition “With”) and deactivated (condition “Without”) during ascending and descending stairs; SD—standard deviation; SE—standard error.

Table 2. Descriptive statistics of ascending and descending stairs.

		Condition		Ascending Stairs			Descending Stairs		
		N	NSFB	Mean	SD	SE	Mean	SD	SE
TIME (s)	20	20	With	7.413	1.246	0.278	7.291	1.691	0.378
			Without	10.072	0.476	0.106	10.558	1.138	0.254
With			0.082	0.012	0.002	0.085	0.016	0.003	
Without			0.059	0.002	0.000	0.057	0.009	0.002	

Note: NSFB—neural sensory feedback activated (condition “With”) and deactivated (condition “Without”) during ascending and descending stairs; SD—standard deviation; SE—standard error.

Figures 3 and 4 show the time and speed for ascending and descending stairs, respectively, in conditions with (_NSFB) and without neural sensory feedback.

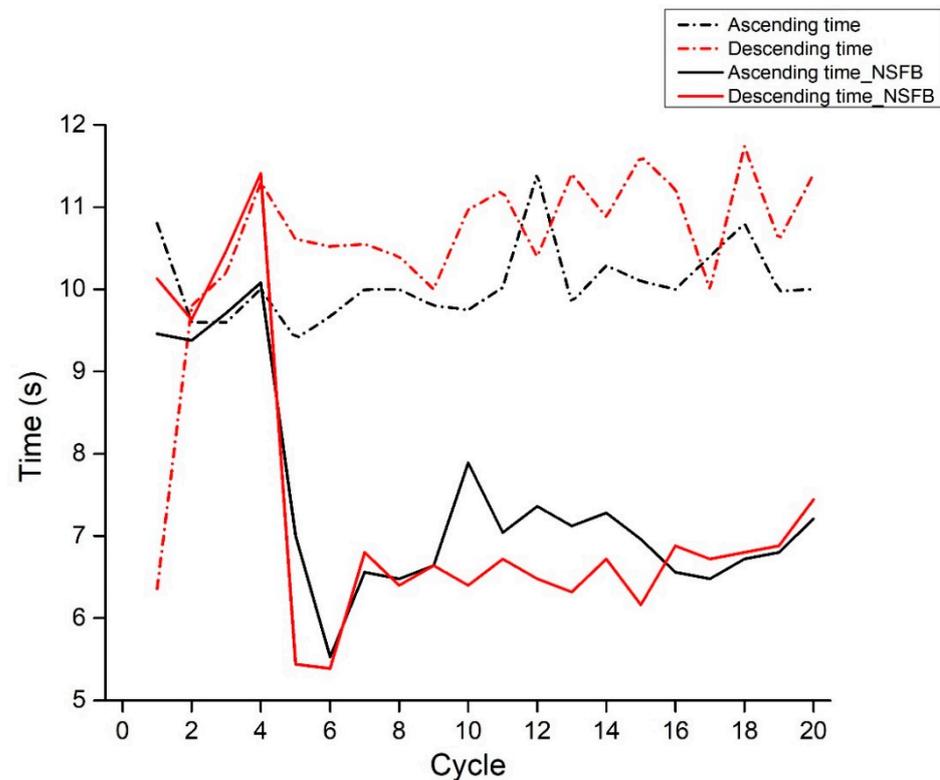


Figure 3. Time for ascending and descending stairs in conditions with (_NSFB) and without neural sensory feedback. *Note:* _NSFB—neural sensory feedback activated (condition “With”) and deactivated (condition “Without”) during ascending and descending stairs.

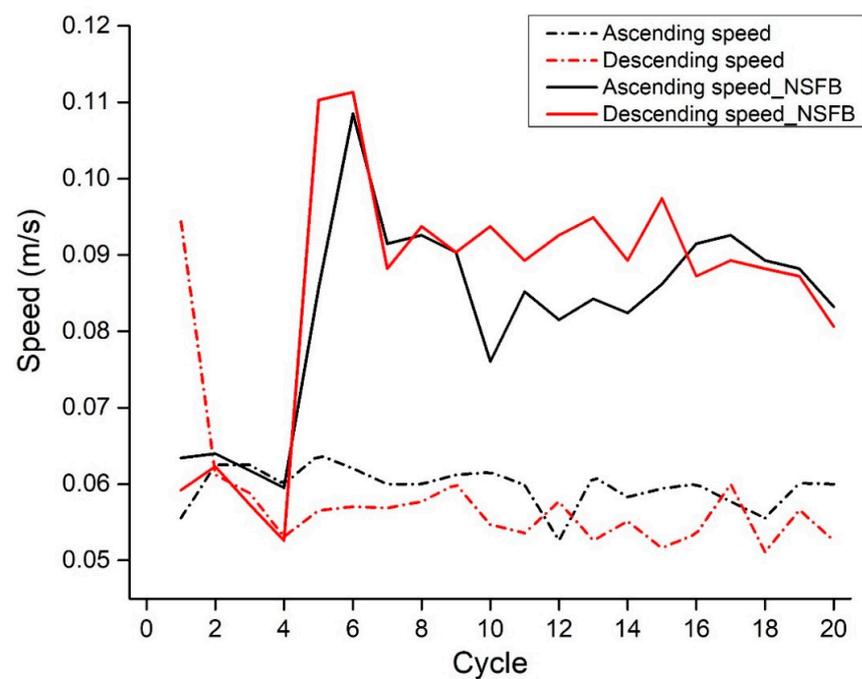


Figure 4. Speed of ascending and descending stairs in conditions with (_NSFB) and without neural sensory feedback. *Note:* _NSFB—neural sensory feedback activated (condition “With”) and deactivated (condition “Without”) during ascending and descending stairs.

Differences in the stance phase, time, and speed between the healthy and the prosthetic leg in conditions with (_NSFB) and without neural sensory feedback were calculated using paired-sample *t*-tests, and results are presented in Table 3, Table 4, and Table 5, respectively.

Figures 3 and 4 clearly illustrate significant improvements in the observed parameters (TIME and SPEED) in favor of NSFB, as indicated by the noticeable differences between the red and black lines. These observations are further supported by the results of the paired-sample *t*-tests.

Based on the results obtained in the significance (Sig.) column that serves to determine the persistence of a statistically significant difference between conditions with (_NSFB) and without NSFB in the examined parameters (Tables 2 and 3), it can be concluded that for both parameters, i.e., TIME and SPEED, the difference between these two extremities was at the highest level ($p = 0.00$).

Table 3. Differences in the stance phase between the healthy and the prosthetic leg in conditions with (_NSFB) and without neural sensory feedback calculated using paired-sample *t*-tests.

Pair	STANCE (s)	Mean	SD	<i>t</i> -Test	df	Sig. (2-Tailed)
1	A_STANCEH	4.140	0.316	14.635	19	0.000
	A_STANCEP	3.086	0.361			
2	A_STANCEH_NSFB	3.783	0.399	3.373	19	0.003
	A_STANCEP_NSFB	3.346	0.402			
3	A_STANCEH	4.140	0.316	4.678	19	0.000
	A_STANCEH_FB	3.783	0.399			
4	A_STANCEP	3.086	0.361	−2.919	19	0.009
	A_STANCEP_FB	3.346	0.402			
5	D_STANCEH	3.886	0.275	4.900	19	0.000
	D_STANCEP	3.413	0.302			
6	D_STANCEH_NSFB	3.686	0.288	8.252	19	0.000
	D_STANCEP_NSFB	2.988	0.261			
7	D_STANCEH	3.886	0.275	3.734	19	0.001
	D_STANCEH_NSFB	3.686	0.288			
8	D_STANCEP	3.413	0.302	8.799	19	0.000
	D_STANCEP_NSFB	2.988	0.261			

Note: A_STANCEH_NSFB—stance phase of the healthy leg during the ascending cycle with (_NSFB) and without neural sensory feedback in s; A_STANCEP_NSFB—stance phase of the prosthetic leg during the ascending cycle with (_NSFB) and without neural sensory feedback in s; D_STANCEH_NSFB—stance phase of the healthy leg during the descending cycle with (_NSFB) and without neural sensory feedback in s; D_STANCEP_NSFB—stance phase of the prosthetic leg during the descending cycle with (_NSFB) and without neural sensory feedback in s.

Table 4. Differences in time between conditions with (_NSFB) and without neural sensory feedback calculated using paired-sample *t*-tests.

Pair	TIME (s)	Mean	SD	<i>t</i> -Test	df	Sig. (2-Tailed)
1	A_TIME	10.072	0.476	8.860	19	0.000
	A_TIME_NSFB	7.413	1.246			
2	D_TIME	10.558	1.138	6.128	19	0.000
	D_TIME_NSFB	7.291	1.691			

Note: A_TIME_NSFB—ascending time with feedback in s; A_TIME—ascending time without feedback in s; D_TIME_NSFB—descending time with feedback in s; D_TIME—descending time without feedback in s.

Table 5. Differences in speed between conditions with (_NSFB) and without neural sensory feedback calculated using paired-sample *t*-tests.

Pair	SPEED (m/s)	Mean	SD	<i>t</i> -Test	df	Sig. (2-Tailed)
1	A_SPEED	0.060	0.003	−8.203	19	0.000
	A_SPEED_NSFB	0.083	0.012			
2	D_SPEED	0.058	0.009	−5.843	19	0.000
	D_SPEED_NSFB	0.086	0.016			

Note: A_SPEED_NSFB—ascending speed with feedback in s; A_SPEED—ascending speed without feedback in s; D_SPEED_NSFB—descending speed with feedback in s; D_SPEED—descending speed without feedback in s.

According to the results of the paired-sample *t*-tests presented in Table 3, it can be concluded that there were statistically significant differences in the STANCE parameter between the compared conditions (with and without NSFB) in both directions (ascending and descending).

In conditions without NSFB, the stance of the healthy leg was longer compared to the stance of the prosthetic leg in both directions ($p_{\text{ascending}} = 0.000$, $p_{\text{descending}} = 0.000$). Similar results were obtained in conditions with NSFB ($p_{\text{ascending}} = 0.003$, $p_{\text{descending}} = 0.000$).

The stance of the healthy leg was longer in conditions without NSFB than in conditions with NSFB in both directions ($p_{\text{ascending}} = 0.000$, $p_{\text{descending}} = 0.001$). The same situation was observed in the case of the prosthetic leg in the descending direction ($p = 0.000$). However, in the case of the prosthetic leg in the ascending direction, the opposite conclusion was reached ($p = 0.009$).

According to the results of the paired-sample *t*-tests presented in Table 4, it can be concluded that there were statistically significant differences in the TIME parameter between the compared conditions (with and without NSFB) in both directions (ascending and descending). The time was significantly shorter in conditions with NSFB ($p_{\text{ascending}} = 0.000$, $p_{\text{descending}} = 0.000$).

Similarly, according to the results of the paired-sample *t*-tests presented in Table 5, it can be concluded that there were statistically significant differences in the SPEED parameter between the compared conditions (with and without NSFB) in both directions (ascending and descending). The speed was significantly greater in conditions with NSFB ($p_{\text{ascending}} = 0.000$, $p_{\text{descending}} = 0.000$).

The respondent's walking pattern resembled that of healthy individuals more closely in conditions with NSFB.

4. Discussion

Our results indicate that high-reversal cortical plastic changes occur in conditions with NSFB, leading to a significant improvement in the patient's stance, time, and speed when ascending and descending stairs compared to conditions without NSFB. The respondent started ascending with their healthy leg as the swing leg and descending with their prosthetic leg as the swing leg, both in conditions with and without NSFB. Without NSFB, the patient is limited to visual guidance only and left without proprioceptive information about the prosthetic leg, guiding them to an asymmetrical gait, increased fatigue and brain effort, and reduced mobility [32].

The results obtained in conditions without NSFB are supported by the fact that when climbing stairs, the respondent must overcome an obstacle of a certain height without feeling flexion in the knee joint of the prosthetic leg. Once the foot is on the step, the patient exerts unnatural hip extension torque to keep the prosthetic knee fully extended against the end stop, while they pull themselves up the step using their upper body strength [33]. For this reason, the amplitude of the movement is greater to prevent unwanted contact with an obstacle (stairs) and a fall or injury. This kind of movement requires more time to master, as well as energy.

The situation when going down is different because there are no obstacles to cross and the person has to “slide” the prosthetic leg to the next step to overcome the previous one; thus, less time is needed. However, this unnatural stair descent strategy is inherently risky because the prosthetic foot can easily slip off the edge of the step, causing the person to fall because (a) the limited ankle range of motion in the prosthetic leg does not allow the foot to be placed flat on the step during stance in descent and (b) the person needs to place their foot on the edge of the step, pivoting on the prosthetic foot as they roll their body forward while the knee flexes [33].

We determined a significant reduction in the stance phase of ascending and descending stairs in conditions with NSFB in both the prosthetic and the healthy leg of the respondent. Our results indicate a faster load shift from one leg to the other that occurred in conditions with NSFB versus conditions without NSFB, with the significance ranging from Sig. = 0.000 to Sig. = 0.009, due to a higher level of confidence and restored the proprioceptive ability of the respondent to define the position of their leg in relation to the ground, as explained by Valle et al. [27]. This consequently enabled the respondent to transition faster from heel strike to toe-off [34].

The significantly reduced time (Sig. = 0.000), i.e., the increased result of speed (Sig. = 0.000) obtained in our study in conditions with NSFB versus conditions without NSFB, is consistent with the findings of Preatoni et al. [33], who explained the increase in walking speed in conditions with NSFB by the absence of a cognitive burden.

NSFB in a leg prosthesis, such as that described in our study, has been proven to increase the overall experience in people with above-the-knee (transfemoral) amputation [25].

5. Conclusions

The main limitation of our research is a lack of a larger population of respondents. However, low sample sizes are typical in research involving individuals with above-the-knee amputations and surgically implanted electrodes that stimulate somatosensory nerves, since finding volunteers who meet the study requirements is challenging. Additionally, in this paper, we focused solely on gait kinematics and did not explore the relationships between the participant’s cognitive, physical, and gait kinematic parameters.

Based on the results obtained, we demonstrated that gait stance, time, and speed when ascending and descending stairs can be controlled and tailored in real time through NSFB. The improved gait performance in conditions with NSFB suggests that further gait training can lead to additional reduction in gait asymmetry between healthy and prosthetic extremities.

Future studies should aim to explore the effects of NSFB and gait-training interventions across a larger and more diverse sample, encompassing individuals from different age groups, with different activity levels, and with various prosthetic designs. This will help evaluate the generalizability of the findings and identify potential variations in treatment outcomes.

Author Contributions: Conceptualization, S.B., M.R., D.S., S.M. and F.M.P.; methodology, S.B., M.R., D.S., S.M. and F.M.P.; software, S.B., M.R., D.S., S.M. and F.M.P.; validation, S.B., M.R., D.S., E.P., A.L., N.A., I.B., T.D., B.B., I.Ć., S.M., F.M.P., Š.S., M.T. and F.V.L.; formal analysis, M.R., D.S. and F.M.P.; investigation, S.B., M.R., D.S., S.M. and F.M.P.; resources, E.P., A.L., I.B., T.D., I.Ć., S.M., F.M.P. and F.V.L.; data curation, N.A., B.B. and M.T.; writing—original draft preparation, S.B., M.R., D.S., N.A., T.D., B.B., Š.S., M.T. and F.V.L.; writing—review and editing, S.B., M.R., D.S., E.P., A.L., N.A., I.B., T.D., B.B., I.Ć., Š.S., M.T. and F.V.L.; visualization, S.M., F.M.P., E.P., A.L., I.B., I.Ć., Š.S. and M.T.; supervision, S.M., F.M.P., E.P., A.L., I.B., I.Ć. and M.T.; project administration, S.B., M.R., D.S., S.M. and F.M.P.; funding acquisition, S.B., T.D., S.M., F.M.P. and F.V.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia within the project OI179024.

Institutional Review Board Statement: The Ethics Committee of the Faculty of Medicine, University of Belgrade, approved the study protocol in accordance with the Declaration of Helsinki for human research (approval number 29/XII-18, Belgrade, Prof. Dr. Sanja Mazić).

Informed Consent Statement: Informed consent was obtained from the subject involved in the study.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to privacy of the included subject.

Acknowledgments: We acknowledge support from the European Commission under the H2020-EIC-FTI-2018-2020 GoSafe (grant agreement no. 870144).

Conflicts of Interest: The authors declare no conflict of interest.

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