ORIGINAL ARTICLE

# FEEDBACK SYSTEM FOR PHYSIOTHERAPY AND POPULAR ATHLETES

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## ABSTRACT

***Background:*** Feedback systems give support to athletes or patients and have a positive effect on training control. A feedback system, the virtual coach (VC), was developed.

***Methods:*** Two different studies in both fields of application (popular sport, rehabilitation) were conducted. The push-up-study was done to investigate the effect of the VC during a 6-week-training.

***Results:*** The results show the positive impact on different parameters, such as motion duration which is closer (EG: 3.13 (± 0.28) s, CG: 1.88 (± 0.4) s) to the three seconds motion duration prescribed in the training routine for the EG (using the VC) compared to the CG (without feedback). The second study addressed the second field of application - the rehabilitation. Eight subjects (transfemoral amputees) conducted an 8-week-training with a particular training device added by mobile sensors and the VC (com-bined system). The gait, the maximum power of hip muscles and the weight distribution war registered before and after the intervention. The results are individual as the subjects are. The improvement of the maximum power (range: 18.6 to 26 %) and the gait velocity (range: 0.05 to 12.39 %) are the most remarkable results. Positive changes in other gait parameters as well as in the weight distribution were observed for the individuals.

***Conclusion:*** Summarizing both studies, a positive effect of using the feedback system (VC) can be found. Due to the small sample size and the heterogeneity of the amputee group, a generalized statement cannot be given from the second study with the transfemoral amputees.

***Keywords:*** feedback system, virtual coach, rehabilitation, training support, popular sports.

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## INTRODUCTION

Different feedback systems are used in the field of sports and rehabilitation. These systems have a supportive character for athletes and patients, whose impact should not be underestimated. The use of such systems is successful by showing a positive effect on training control [1,2]. Furthermore, feedback systems can help to reduce the risk of injury [3] and to improve the performance during different movement tasks (e.g., balance) of elderly people [4]. Feedback can be given in different ways, as visual, auditory, haptic or as various combinations of the mentioned types. The type of feedback has to be chosen in the dependence of (1) the field of application, (2) user profiles and (3) requirements [5].

Transtibial and transfemoral amputees show different gait deviations, which are varying in degree with the amputation level. Transfemoral amputees have more significant problems than transtibial amputees [6,7,8,9]. The reasons for the appearing gait problems have been caused by the amputation itself resulting in biomechanical changes. These changes influence the static and dynamic balance control. Gait asymmetries are the result of muscular dysbalance [10] or atrophied muscles [11,12,13]. The hip abductors are affected and showed a quick degeneration [11,13,14,15]. Based on a strength training combined with stretching methods of the affected hip, gait deviations can be reduced [13,16,17,18,19]. The effectiveness of such home-based training sessions can be increased by using sensor-based computer systems giving feedback to the exercising person.

The aim was to develop a feedback system, which can be used as a virtual coach (VC) in both fields: popular sport and rehabilitation. The purpose of the development was to give sensor-based feedback to a subject (e.g., sportsman, patient) during exercise in the absence of a human coach. The first technical realization was shown in Orlowski et al. [20]. The current paper focusses on two different applications of the VC in the field of popular sport and rehabilitation. The first application refers to the training of push-ups. The second application is giving feedback to transfemoral amputees exercising the hip muscles with a mobile training device. Both groups of subjects are getting feedback based on two inertial sensors, which are fixed on two body segments linked by a joint (lower/upper arm, 2: upper leg/trunk). The changing of the joint angle (in a defined plane), as well as a specified threshold, is given as feedback (visual and auditory).

The **first study (I)** presented is an evaluation of the VC. The push-up study presents the usage of the VC in the athletic setting of a popular sport. The impact of the feedback system on the training control is examined.

The **second study (II)** addresses the therapeutic setting. The amputees conducted a strength training with the mobile training device (developed by Guenther Bionics GmbH) added by the VC. The strength-training equipment consists of two cuffs made from hard plastic, which is connected by a joint with a torsion spring. One of the cuffs is fixed to the lower trunk, while the other cuff is mounted to the amputation stump. The integrated joint is located at hip joint height. The hip flexors, extensors, and abductors can be trained with the device. That study aimed to examine the effect of an 8-week-training with the combined system (mobile training device and VC).

**Push-up study**

## MATERIALS AND METHODS

In the push-up-study 29 subjects (20 m, 9 f, age: 22.9 ± 4.0 years; weight: 74.9 ± 11.6 kg and height: 177.6 ± 8.4 cm) took part and conducted a 6-week training of push-ups (two sessions each week, in total twelve sessions). The subjects were divided in the experimental group (EG, with feedback (VC)) and control group (CG, without feedback).

Figure 1 shows the graphical user interface of the VC for the athletic setting during the push-up training, which is used by the EG as shown in Figure 2. For both groups (EG and CG) the motion of the subject while doing push-ups was captured with two inertial sensors. The raw acceleration and the derived joint angle (elbow) were stored for further analysis — the used training routine based on the training example of the Men's Health Magazine given by [21], which was designed to reach 100 push-ups in seven weeks. The training routine is strongly oriented with the High-Intensity Training (HIT). The corresponding level of the training routine was selected based on the pretest result. During the pretest, the number of correct push-ups was determined for each subject.

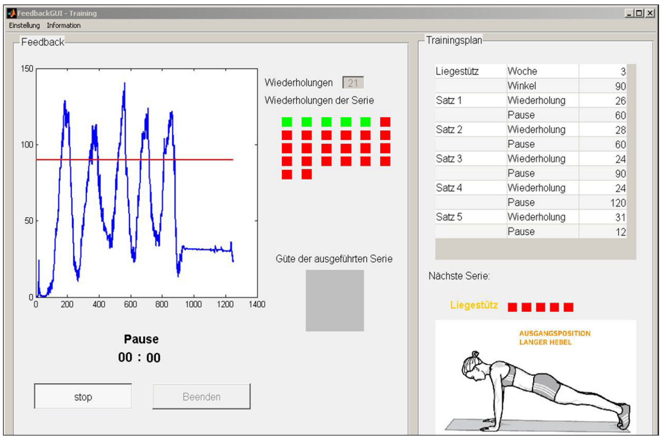


**Figure 1:** Graphical user interface of the virtual coach with real-time feedback on the left side (changing angle of the elbow while doing push-ups); the current training routine of the user as well as information about die current series on the right side.

**Figure 2:** Push-up study training setup: The subject wears the two inertial sensors on the left or right arm. The VC is running on the notebook in front of the subject giving a visual (changing elbow angle) and auditory feedback (achieving the given threshold, 90° elbow angle).

During the offline analysis based on the developed algorithm in MATLAB™ (TheMathworks Inc., Natick, MA, USA), the following parameters were calculated from the stored data of both groups:

- Motion amplitude,
- Duration of motion,
- Repetition number, and
- Break period.

For each parameter, the absolute and relative deviation from the respective target value was determined and compared with descriptive and inferential methods. During the pre- and posttest, the number of push-ups was determined. That parameter was used to assess the effect of the training, which was instead the secondary focus of the study. The benchmark for each session of all subjects were tested for normal distribution by using the Kolmogorov-Smirnov test. Depending on the result, the t-test for independent samples or the Mann-Whitney-U-test was applied. To investigate the difference of the parameters regarding the given target value the t-test for a dependent sample or the Wilcoxon test was used. The level of significance was set to $\alpha = 0.05$. The statistics were done with IBM SPSS Statistics Version 23 (IBM, Armonk, USA).

## RESULTS

Regarding the break periods given by the instructor of the study, significant differences were found for the control group. In most cases, the break time was much longer. The relative mean deviation between the prescribed and the conducted break was 71 % (see Table 1). Because the specified break time is integrated with the feedback system (VC) and the user of the VC starts the next exercise series immediately after the break, the registered deviations for the EG is almost zero.

Furthermore, the parameter duration shows significant differences from the specifications prescribed in the training routine (3 s, see Table 1). On average, the push-ups were conducted too fast with 1.88 s by the CG, while the EG has a mean motion duration of 3.13 s. Also, the SD of that parameter shows that the EG performs the move closer to the specification than the CG (0.28 s vs. 0.4 s)

Regarding the execution quality of the push-up, the differences between the two groups were apparent shown by the parameter motion amplitude. The EG reached or even exceeded the demanded angle of 90 deg significantly in the elbow joint (motion amplitude difference of 20.10 % (± 8.94 %)). On average, the same applies to the CG having a percentage difference of 2.69 %. However, the reached mean motion amplitude of 92° is not significantly different from the target value of 90°. Furthermore, the large SD of the parameter (± 17.45 %) points to the fact that in most cases the subjects did not reach the needed angle.

The number of repetitions is given in Table 1 as relative to the repetition number prescribed in the training routine. It can be noted that the CG finished the demanded number of push-ups with little deviations (0.2 ± 2.88 %), while the EG on average conducted 6.18 % more repetitions (SD: ± 6.03 %).

**Table 1:** Mean and SD of the different parameters of both groups (EG and CG) as well as the given target value of the different parameters (* significant difference to the target value, p < 0,001). The p-values refer to the investigated difference between both groups. The parameters motion amplitude, repetitions and break period are given as a relative value in relation to the target value.

| Parameter | EG Mean (± SD) | CG Mean (± SD) | Target value | p-value (EG vs KG) |
|---|---|---|---|---|
| **Motion amplitude (%)** | 20.10* (± 8.94) | 2.69 (± 17.45) | 90 deg | < 0.001 |
| **Motion duration (s)** | 3.13* (± 0.28) | 1.88* (± 0.40) | 3 s | < 0.001 |
| **Repetitions (%)** | 6.18* (± 6.03) | 0.20 (± 2.88) | According to individual training routine | < 0.001 |
| **Break period (%)** | ~ 0 | 71.02* (± 34.96) | Individual: (60, 90 or 120) s | < 0.001 |

The maximum number of push-ups determined during pre- and posttest changed similarly for both groups (EG: 25.9 (± 9.6) to 35.8 (± 7.5), difference 9.9; CG: 26.2 (± 10.6) to 36.7 (± 13.3), difference 10.5). The EG showed on average an improvement of 38.1 %, and the CG improved the number of push-up by 40.1 %. The difference between the observed improvement in terms of the maximum number of push-ups between both groups is not significant (p=0.81).

## DISCUSSION

As expected, both groups (EG and CG) increased the maximum number of push-ups after the 6-week training intervention. It was assumed, that the parameters break time and motion duration differ from the prescribed specifications of the training routine for the CG. The presented results confirm that assumption. In contrast, the parameter number of repetitions show only little deviations from the given repetition number for the CG, but larger and significant differences for the EG. The found difference regarding the repetition number can be justified in the usage of the feedback system (VC) and the strict requirements of the VC. The VC counts a repetition when the given threshold, a minimum angle of 90 deg, is exceeded and the temporal distance to the previous repetition is at least 2.5 seconds. The VC does not accept faster movements or lower motion amplitudes. Especially during the first training sessions, the subjects of the EG have to get accustomed to the new training situation and the feedback given by the VC. During that period of familiarization, they did push-ups, which are not accepted by the VC. In the offline analysis of the captured data, these repetitions are detected and counted as well.

Nevertheless, the VC supported the training control successfully, because of the better results of the two parameters break time and motion duration, which are more important for the training. These results confirm the positive effect of the feedback.

In future development, it is intended to adapt the VC to the needs of the users based on the experiences from that study. A possibility is to give more detailed feedback to the user by using gyroscopes and magnetic field sensors among acceleration sensors [3]. To improve the motion duration during the push-up and consequently to prevent the problem with the not counted repetitions, it is conceivable that a rhythm based on a metronome is produced to give auditory feedback [22]. Possibly, it is recommended to use a higher frame rate to have more information per seconds, if the motion of other athletic exercises is faster [3,4].

**Study with transfemoral amputees**

## METHODS AND MATERIALS

In the second study, six transfemoral amputees (2 w, 4 f, age: 54.1 ± 12.5 years, body weight: 92.9 ± 13.9 kg, body height: 176.7 ± 6.3 cm) conducted an individual, adapted 8-week training with a mobile training device and the VC (see Figure 3). Within the scope of the study, different investigations were done, and various parameters were determined during pre- and posttest to assess the effect of the complete system consisting of a mobile training device and feedback system.

1. The gait of the subjects was captured and analyzed with the InvestiGAIT system using four inertial sensors [23]. Two of them were laterally attached above each ankle, one centered on the pelvis and one at the level of the thoracic vertebra Th2 (see Figure 4). The gait was measured on a 15-m straightforward distance, and the subjects completed 20 gait sequences.
2. The maximum voluntary contraction (MVC) was determined as isometric power measurement for the four hip motion (flexion, extension, abduction, adduction) using the HipTor [10]. The measuring started for each direction with a test with approximate 80 % of the full power, which was followed by three repetitions where the subjects were asked to reach their maximum power. The subjects were motivated by showing the real-time power signal captured from the force transducer supplemented by the last reached maximum power as a threshold on a monitor.
3. Using two AMTI force plates (AMTI Force and Motion, Watertown, USA), the weight distribution between both legs was recorded. The subjects stood on the force plates and were asked to hold still and to distribute the weight evenly for 20 seconds (five times).

Selected parameters (MVC, displacements of the pelvis and the upper body, standard gait parameters) were determined before and after the intervention and compared with descriptive and inferential methods.

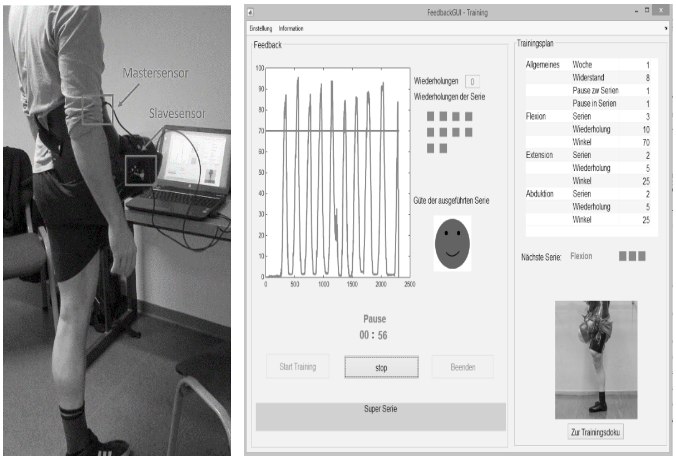


**Figure 3:** A trans femoral amputee during a training session with the mobile training device and the VC running on the notebook (left side). On the right the graphical user interface of the VC for the therapeutic setting for the amputee hip strength training with real-time feedback during the hip motion, flexion, extension, ab- and adduction (left side) as well as the individual training routine of the user and information to the current exercise (right side).

**Figure 4**: Investigation settings. Gait analysis: attachment of the inertial sensors on the subject at the ankle and the upper body for capturing the gait (left and left middle); Weight distribution: position of the subject on the two AMTI force plates for determining the weight distribution between both legs (right middle); MVC measurement: the HipTor for measuring the maximum power of the hip muscles (right).

## RESULTS

After the 8-week training, the maximum power (MVC) was improved by 87.5 % of the subjects. On average, the MVC of the flexors showed with 26.0 % the best improvement (see Figure 5). While all the subjects increased the power of the hip flexors and extensors (see Figure 6), three subjects showed a decreased power of the hip adductors or abductors in the posttest, respectively. However, the power of the hip abductors improved by 19.1 %.

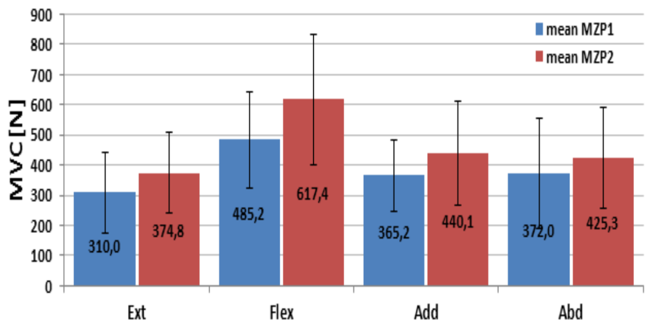


**Figure 5:** MVC (in N) of the sample (6 TF-amputees) at pre- and posttest for the four considered motion of the hip: extension, flexion, adduction and abduction.

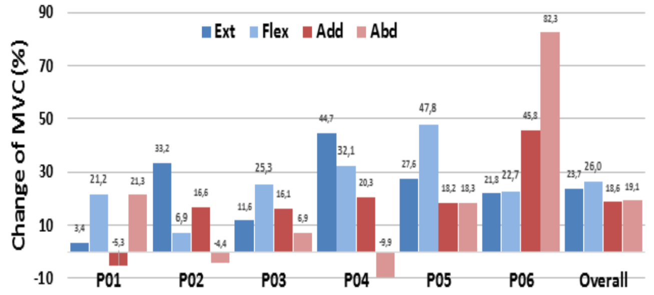


**Figure 6:** Change of MVC (%) after 8-week training for each individual subjects as well as overall for the sample for the four considered motion of the hip: extension, flexion, adduction, and abduction.

Table 2 gives an overview of the standard gait parameters. Little to moderate differences are visible, but the calculated p-values indicate that only the differences found for the parameters velocity and step length (sound leg) are significant. The velocity during walking was improved by all subjects with a range of 0.05 to 12.39 %, which was significant in the three subjects.

**Table 2:** Gait parameters for the sound and affected (pro) leg of the test subjects (six amputees) as mean and SD for the pre- and posttest. The determined p-value is showing the significance of the differences between the pre- and posttest.

| Parameter | Mean (± SD) Pre | Mean (± SD) Post | p-value |
|---|---|---|---|
| velocity (m/s) | 1.11 (± 0.30) | 1.15 (± 0.29) | < 0.05 |
| cadence (1/min) | 101.46 (± 13.84) | 102.26 (± 13.40) | 0.123 |
| Step length (m) pro | 0.69 (± 0.15) | 0.72 (± 0.17) | 0.232 |
| Step length (m) sound | 0.80 (± 0.13) | 0.83 (± 0.11) | < 0.05 |
| Swing phase (%) pro | 46.42 (± 5.22) | 46.33 (± 5.74) | 0.956 |
| Stance phase (%) pro | 53.58 (± 5.22) | 53.67 (± 5.74) | 0.956 |
| Swing phase (%) sound | 37.85 (± 4.37) | 37.39 (± 5.05) | 0.460 |
| Stance phase (%) sound | 62.15 (± 4.37) | 62.61 (± 5.05) | 0.460 |

Because the considered group is small, an individual review is necessary. Figure 7 shows the change of the relation between stance and swing for two chosen subjects. The subject P01 has remarkable deviations during pretest (48.5 to 51.5 %) from the natural relation of stance and swing (60 to 40 %) [24]. After the intervention, the stance-swing ratio normalized to 58.5 % to 41.5 %, which marks a positive effect of the intervention. The subject P05 has a normal relation of swing and stance (41.7 to 58.3 %) during the pre-test. The changes observed after the intervention are small (42.2 to 57.8 %).

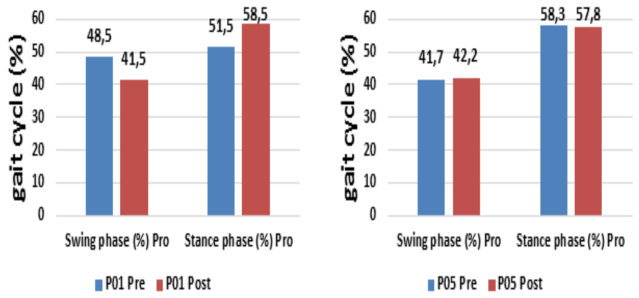


**Figure 7:** The gait parameters swing and stance for two of the subjects (P01, P05) for the pre- and posttest.

The movement of the upper body was registered. The range of motion (ROM) of the pelvis and the shoulders are determined. Table 3 refers to ROM of the pelvis' rotation around the sagittal axis. Mean, and SD was calculated from at least 15 gait sequences. The difference between both tests (pre, post) is given as a relative value, which is significant for five subjects. Two subjects (P05, P06) show a significant reduction of the ROM.

**Table 3:** Rotation of the pelvis around the sagittal axis (roll) as range of motion (ROM) of the six subjects at pre- and posttest and relative difference between pre- and posttest. Reference values ([a]Saunders et al. (1953), [b]Sjöhdahl et al. (2003), [c]Goujou-Pillet et al. (2008), [d]Orlowski et al. (2017)). Significant differences between pre- and posttest are marked with ** ($p < 0.01$).

| | Test | Mean (± SD) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | P01 | P02 | P03 | P04 | P05 | P06 | Ref. |
| ROM_ Pelvis Roll [deg] | pre | 7.52 (±1.08) | 5.81 (±0.35) | 6.73 (±0.43) | 3.27 (±0.20) | 10.24 (±0.71) | 12.24 (±1.54) | 7[a] 8[b,c] 5[d] |
| | post | 8.87 (±0.07) | 6.36 (±1.35) | 7.37 (±0.28) | 2.73 (±0.19) | 8.57 (±0.73) | 9.50 (±1.09) | |
| | Diff [%] | *17.94*** | 9.45 | *9.54*** | -16.43** | *-16.30*** | -22.40** | |

The weight distribution of the six subjects is presented in Figure 8. A positive value shows a higher load on the sound leg, while a negative value means a higher load for the artificial limb.

The subjects P02 and P05 charged more weight on the artificial leg (P02: -4.0 %, P05: -4.1 %), which is increased in the posttest (P02: -10.6 %, P05: -10.7 %). Two subjects (P01, P06), having a high load on the sound leg, showed reduced values in the posttest (P01: 19.3 to 13.9 %, P06: 19.4 to 11.5 %), while the other subject P04 increased the load (P04: 5.0 to 9.6 %). Subject P03 has a balanced weight distribution during pretest and posttest (0.9 - 1.6 %).

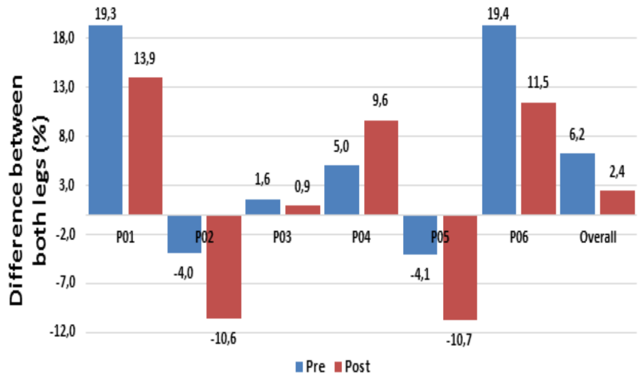


**Figure 8:** Weight distribution of the six amputees and as mean for the whole group for the pre- and post-test.

## DISCUSSION

The presented results of the different investigations show various changes in the single parameter (MVC, gait parameters and weight distribution) which are individual for each amputee.

After the training intervention with the complete system (training device and VC), positive changes are shown for the maximum power of the hip flexors, extensors, abductors, and adductors for nearly all subjects. The best improvement was determined for the hip flexors with an increase of 26.0 %. Nevertheless, the other hip muscles have a power growth with approximately 20.5 % (range: 18.6 - 23.7). Even if the resistance of the training device was not appropriate for all subjects, the results show that the intervention provides a sufficient stimulus. However, most of the subjects took part in the pilot study or other pretests and were familiar with the test set, it can be excluded that the increase of the strength is based on learning effects [25].

Furthermore, it can be neglected that the motivational effect described by Hopkins [25] has an impact on the results because the subjects did not know their findings of the pretest. Regarding the transfemoral amputees and their hip muscles corresponding strength deficits and dysbalances were observed as described in the literature, unless they are not as pronounced as in other amputees. Guenther [26] found for transfemoral amputees that (1) the hip flexors are always stronger than the hip extensors and (2) the hip abduction power is still larger than the adduction power. The first phenomenon was also observed for the tested samples, but the second was not reflected in the MVC results.

As the results of the gait analysis show, there are some improvements after the intervention. Nevertheless, the changes are rather individual as each subject, and its situation (length of the amputation stump) is. All subjects improved the gait velocity, which is a sign of positive development of the locomotion system because there is a direct relation between the gait velocity and the muscle strength of the locomotor [27]. The improvement was significant for the group of amputees as well as for three of the subjects. The gait velocity of the subjects considered as mean is faster as reported from other studies (0.82 m/s - 1.05 m/s) [14,28,29,30,31]. Tura et al. [32] determined merely a comparable gait velocity for their subjects of transfemoral amputees. The given standard deviation (0.3 m/s) shows that the range between the subjects is also very large. There are three groups of gait velocities within the current study: (1) 0.66 - 0.83 m/s, (2) 1.23 - 1.37 m/s, and (3) 1.41 m/s. Similar results are visible for the gait parameter cadence, which is also, with the exception of the two subjects (83.6 to 89.3 steps per minute), larger than determined in other studies.

An asymmetric relation of swing and stance phase was observed before and after the intervention for the subjects with one exception, subject P05 (see Figure 7). Nevertheless, the asymmetries in that parameter are not pronounced as in other studies [30,33]. The higher velocity observed for the subjects is a reason for the smaller deviations because the relation of swing and stance phase depends on the gait velocity [24]. Furthermore, different studies show an asymmetry of step length between the sound and the affected leg. Beckers and Deckers [7] pointed out that the step length of the prosthetic limb can be either longer or shorter than the step length of a sound leg. The reason for the difference is an insufficient hip extension during the stance or a want of confidence in the prosthesis. Different studies [31,34,35] determined a larger step length for the prosthetic leg while the tested subjects have a larger step length on the sound limb.

Significant differences were determined for the motion of the upper body, especially for the pelvis regarding the roll angle (rotation in the frontal plane). Sjöhdahl et al. [36] and Goujon-Pillet et al. [37] examined the gait of amputees in comparison to healthy subjects. The healthy subjects had a mean ROM for the roll angle of 8°. Considering that value, two subjects (P05 and P06) show deviations from that reference during pretest. Both subjects could reduce the ROM, which is nearly in the range of the used reference after the intervention (see Table 3).

Additionally, Table 3 gives a reference value that is determined for healthy subjects with the InvestiGAIT system. Using that value as a reference, four (P01, P03, P05, and P06) amputees have deviations in the considered gait parameter. The observed changes after the intervention are positive in two cases (P05 and P06), negative for the other two subjects (P01 and P03) and also for the subject P02 whose ROM is larger in the posttest (6.4°) compared to the pretest (5.8°).

The presented results of the weight distribution show that most of the amputees charge their sound leg stronger which is in agreement with Ku et al. [38] and other research groups [39,40]. Consequently, the weight is not balanced between both legs. The results found for the test subjects confirm at large the statements of the literature: Hlavackova et al. [39] determined a distribution of weight of 55 to 45 % between sound and affected leg in a group of eight amputees; Nederhand et al. [40] showed a similar distribution of 54 to 46 %. Considering the mean values of the considered group of six subjects (see Figure 8) before (difference of 6.2 %) and after the intervention (difference of 2.4 %), the improvement is visible.

## CONCLUSION

Summarizing both studies, a positive effect of the training and a supporting effect of using the feedback system (VC) can be found. The positive impact is shown by positive changes of different parameters in both studies. In addition to objective parameters, the subjective views and impressions of the subjects of both studies were collected using questionnaires. The answers and hints of the subjects were throughout positive. They showed that the feedback system (VC) had a motivating effect to do the training. Nevertheless, it has to be noted that a generalized statement cannot be given from the second study with transfemoral amputees due to the small sample size and the heterogeneity of the group. Further research with a larger group of transfemoral amputees with dividing them in experimental and control group have to be done to draw a definitive conclusion of the effect of the training device and the influence of the feedback system (VC).


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### Ethical Approval

The ethics committee of Otto von Guericke University Magdeburg (Faculty of Medicine) gave the ethical approval (reference number of the ethics protocol: 25/15).


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### Conflict of Interest

All authors declare that there is no conflict of interests.

### Disclaimer

All authors declare that the views expressed in the article are his/her own and not the funders/institutions.

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