Gait Patterns Monitoring Using Instrumented Forearm Crutches

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Abstract. Crutches are one of the most common assistive devices used in rehabilitation for lower limbs. Improper use of them results in extended recovery periods and even cause damage and pain to the limb. Many existing studies demonstrated that correctly using crutches requires an understanding of the disability or injury of the patient, gait patterns as well as user and crutch interaction during rehabilitation. In this work, a prototype was developed to monitor in real-time the exerted axial force and the tilt angles involved in each gait cycle at a prescribed gait pattern. The prototype is composed for an instrumented forearm crutch with a wireless measurement system. Four gait patterns were tested experimentally in three healthy users. Promising results were obtained that induces the possibility to identify automatically the performed pattern and even typical errors while using forearm crutches. The proposed system opens up a valid alternative to individualize therapy by monitoring the user gait using crutches in the rehabilitation process.

Keywords: Assistive technologies · Forearm crutches · Crutch gait · Gait monitoring · Instrumented crutch

1 Introduction

Forearm crutches or elbow crutches are assistive devices designed to help individuals walk with reduced Weight-Bearing (WB) on the affected lower extremity. These devices also have the function to improve balance, to assist the propulsion, to reduce the compressive force on one or both lower limbs and can help relieve pain in the affected limb [6, 7].

Sensorized devices can provide objective and quantitative data to adapt the therapy to the patient, to monitor the daily activities, and to assess the recovery status of the user. It is significantly recognized that the improper use of crutches may lengthen the rehabilitation period or even cause further damage [6, 9, 11]. In general, this problem can be tackled by using instrumented crutches to monitor the involved parameters during the gait. For instance, the axial force allows knowing the support needs of the patient and also, the crutch motion represents relevant information for the therapist to define the gait performance.
Consequently, the monitoring of these variables can instruct the user into the correct use of the crutches during recovery, and avoid other injuries or even a painful experience due to the wrong use of the device.

Walking with any assistive device modifies the gait pattern. Hence, different structures for walking with crutches are pre-established according to specific patient requirements. The literature review shows different prototypes and systems [2,4,5,8,9] with the purpose of analyzing involved variables in walking with crutches. However, these research projects do not present enough information about monitoring the different gait patterns. In order to monitor the behavior of the applied force and the tilt angles into a gait pattern, a system with low cost-sensors was developed and installed on a forearm crutch [9]. The present paper shows the results of monitoring parameters of four gait patterns and the choosed descriptors for the gaits. Moreover, it presents the discussion of the obtained data and possible future works.

2 Gait Training Using Crutches

There are diverse ways to walk with crutches that depend on a specific injury or disability [1,12,13]. Gait patterns rely on the user’s ability to move the feet reciprocally, tolerate full load on each leg, lift the body off the floor by extending the elbows and pressing on the hands, and maintain balance [6]. The structure of gait patterns is defined according to different parameters, including the delay between the crutch and foot placement, the number of points in contact with the ground, and the laterality [1]. In this context, the points indicate the number of floor contacts on a perpendicular line to the direction of walking in one gait cycle, as shown in Fig. 1. Determining which gait is more beneficial depends on

![Image](image.jpg)

Fig. 1. Sequence of gait patterns using forearm crutches. Shaded areas represent WB, numbers show the time frame in the sequence of the gait, when ground contacts land synchronously. Arrows indicate the advance of the foot or the crutch. Modified of [1,3]
the lower-limb strength of the user and the impaired side. For example, Four-point gait is the slowest and the most stable pattern and two-point gait, that is similar to regular gait pattern, is the second slowest gait pattern [12]. During Swing-Through gait, the user lands and pivots over a crutch, repeated and acute stresses of crutch hand/arm support go through the user’s wrist, elbow, and shoulder joints [11], noticeably the energy cost of this pattern is the highest.

Conforming to the literature, a study of crutch gait requires the incorporation of variables to measure the human performance (physical or psychological responses), and dynamic aspects of crutch locomotion during walking. In line with the dynamic parameters, walking with crutches implies the study of the applied forces to the upper limbs, which carry the body during the gait cycle, as well as kinematic measurements. Gait crutch walking includes an understanding of gait variables additionally: angles, displacement, cycle times, phase ratio, step length, cadence velocity and acceleration, as cited in [1,7].

The exerted force, crutch angles and the relationship between the phases within the walking cycle are essential parameters, in order to examine the crutch walk behaviour under prescribed gait patterns. Measurements of time, such as contact time can indicate a gait pattern change. Joint angles show the trajectory of the crutch during walking and phase ratio, or swing/stance ratio compares the relative percentage of each stance or swing portion during one step.

3 Methods

3.1 Instrumented Crutch Description

The prototype consists of one crutch and a wireless measurement system. The axial force applied for the user is sensorized, employing strain gauges. The sensors were integrated and connected in bridge configuration inside the handle of the crutch. The signals pass through a conditioning circuit, consisting of a low pass filter and an instrumentation amplifier (INA 126). Also, the orientation of the crutch is measured by using the BNO080 Inertial Measurement Unit (IMU). Tilt angles (pitch and roll) estimations were sent to the microcontroller. The angles are relative to the body and the ground. Pitch ($\theta$) is the angle between a crutch, and the vertical axis in sagittal plane and roll ($\phi$) is the angle with the ground in the frontal plane.

The microcontroller drives the conditioning, conversion and the wireless transmission of the signals. The components, as mentioned earlier, were assembled on a printed circuit board powered by a 5V, 2600 mAh battery. The entire circuit is inside a box installed under the crutch handle on the outer side. Figure 2 depicts the block diagram of the proposed system. [1]. The central processing unit consists of a standard PC equipped with a Bluetooth receiver to process and record data in real-time. Data were collected, with a sampling frequency of 75 Hz. The magnitude of the force and the tilt angles were calibrated and measured, based on $z$-axis and $x$-axis as seen in Fig. 2 a. By multiple tests and electronic and programming adjustments, the data show good repeatability and linearity in the force measurement.
3.2 Data Processing

After each experiment, the obtained data from IMUs were filtered with a ten-point moving average filter to attenuate the dynamic accelerations. The signal force was smoothed using a Gaussian filter to reduce the effect of noise. As discussed in previous literature, the movement of the crutch can be divided into the Swing and Stance phases [1,11,13]. This segmentation was performed for each gait cycle in order to know the appropriate descriptors for each defined pattern. Segmentation was performed by analyzing the pitch angle signal (after observation and several qualitative and quantitative analyzes of the signal). It was considered that from the lowest position of the angle to the maximum point reached by the crutch, the movement is in the swing phase. When the angle lowers to its lowest position, the stance phase ends. This entire movement corresponds to a walking cycle.

According to the aim of this work, attention was focused in vertical forces, pitch and roll angle, and swing and stance phases. Data was summarized finding mean, median and standard deviation for the data of interest. Finally, the descriptors of each pattern were estimated according to force and temporal parameters: time and force intervals for swing and stance phases, maximum force during a cycle and ratios of force and time between the phases. All the data was validated using an RGBD camera that allowed to support the validity and relevance of the data.
3.3 Experimental Protocol

Experiments were conducted in order to monitor and to identify the behaviour of four crutch walk gait patterns. Three healthy volunteers (mean age ± standard deviation, 27.3 ± 2.5 years; height, 160.4 ± 4.2 cm; weight, 55.3 ± 7.02 kg) participated in this study. Due to the homogeneity of the participants in the experiment, we did not consider it necessary to normalize the measured force. None of the users had any orthopedic condition, or pain that could modify their natural walking patterns, besides none of them ever used crutches. They were instructed and trained to handle the forearm crutches in a proper mode and walk in each gait pattern. Users were asked to use the instrumented crutch with the right arm and to watch four videos where the patterns are explained by physiotherapists. Besides, the experiments were planned according to a Guide [10] and the (Fig. 1). The participants were requested to do the tests three times for three minutes. From 2 to 4 points crutch gait, the users were asked to perform the experiments with Full-Weight-Bearing (FWB), and with Non-Weight-Bearing (NWB) for Swing-Through, which means a single foot landing. Force data was collected concurrently with the pitch (θ) and the roll (φ) angles into the gait cycle. The software contains an algorithm to self-calibrating both sensors after each trial.

4 Results

As pictured in Fig. 3, there are notable differences between each gait pattern tested. In 2-Points for one gait cycle, the maximum force applied for the user happens when the crutch starts to go down until it hits the ground (stance phase). That is when (θ) reaches the minimum value, correspondingly with frame 1 in the sequence in 1. Subsequently, when the left crutch leaves the ground and land on the opposite side, then (θ) is at its maximum (swing phase). The gait cycle repeats throughout the gait. Larger peak forces and bigger motions at angles in the Swing-Through gait compared with 2-Points, 3-Points and 4-Points. The 4-Points pattern is the slowest in its execution since it involves the movement of lower and upper extremities. The appreciable variations in φ angle are due to the movements that the user makes to position the crutch and also the dynamic accelerations.

The results in Table 1 show the summarized data of the ratios of time and force for Swing/Stance phases, in conjunction with the mean and standard deviation of the maximum force during a gait cycle. Smaller values (close to zero) in Swing-Stance time ratio means that more time is spent in the swing phase, while values close or greater than one means that the most extended phase is the stance. Otherwise, smaller values (close to zero) in Swing-Stance force ratio, means that greater force is applied in the stance phase. Therefore, the force values in the swing phase are not relevant. Values close to one or greater than one implies that the force was applied significantly in the swing phase. In general, the time ratios for 2 and 3 points showed significant differences concerning the 4 points and Swing-Through gait. For 4 points and Swing-Through, the time
during stance phase is higher than time for 2 and 3 points gait. Moreover, the values of the ratio force for 2 and 3 points gait are lower than 4 points and Swing-Through. For 4 points and Swing-Through patterns, the force is applied during the two phases, although it continues the largest in the stance phase. The maximum forces reached inside a cycle were 122.02 Kg ± 16.1 for Swing-Trough gait and 94.24 Kg for 4 points. The smaller values were obtained during 2 and 3 points patterns (29.01 Kg ± 8.03 and 29.89± 9.41).

5 Discussion

This study provides the results of monitoring four gait patterns with crutches and their relationship with the chosen descriptors. We hypothetically considered that the measured data could be segmented in the swing and stance phases and thus find descriptors that would automatically identify each gait pattern. However, the segmentation was carried out using the pitch angle and not the force, as proposed [4,5]. With this approach, we obtained satisfactory results within each phase, and that allowed us to make the distinction we wanted to explore. In this work, the obtained force and angles values remained similar in proportion to the results of the studies mentioned above, and the difference is mostly statistical. Interesting details came out when we considered the individual data of each pattern Table1. It is clear that for Swing-Trough is required more force from the upper extremity to perform the movement and maintain the
Table 1. Descriptors for 4 crutch gait patterns.

| Subj | Gait Pattern | Swing/Stance Time Ratio | Swing/Stance Force Ratio | Maximum Force Gait Cycle (Kg) |
|------|--------------|-------------------------|--------------------------|-------------------------------|
|      |              | 0.69                    | 0.14                     | 37.91 ± 5.61; 37.56           |
| S1   | 2 points     | 0.71                    | 0.32                     | 29.89 ± 9.41; 32.34           |
|      | 3 points     | 0.71                    | 0.32                     | 29.89 ± 9.41; 32.34           |
|      | 4 points     | 0.59                    | 0.73                     | 68.84 ± 13.68; 60.94          |
|      | S-T          | 0.51                    | 0.85                     | 122.02 ± 16.11; 119.49        |
|      |              | 0.77                    | 0.36                     | 39.06 ± 5.13; 40.99           |
|      | 3 points     | 0.77                    | 0.36                     | 39.06 ± 5.13; 40.99           |
|      | 4 points     | 0.41                    | 0.69                     | 94.24 ± 19.34; 105.48         |
|      | S-T          | 0.59                    | 0.75                     | 97.71 ± 16.89; 95.69          |
| S2   | 2 points     | 0.62                    | 0.10                     | 29.01 ± 8.03; 29.77           |
|      | 3 points     | 0.69                    | 0.32                     | 29.09 ± 9.58; 32.05           |
|      | 4 points     | 0.38                    | 0.60                     | 54.02 ± 15.42; 60.30          |
|      | S-T          | 0.51                    | 0.73                     | 60.63 ± 19.52; 53.96          |

Notes: The descriptors are indexed as mean ±; median for each gait pattern for 3 subjects. S-T corresponds to Swing-Through gait.

balance. The crutches propel the body forward while the legs are swung to past them. For all the subjects Maximum forces were obtained in this pattern. The graph for 4-Points pattern and the collected data suggest that the segmentation should include more gait phases due to the four movements to complete a cycle, as can be seen in Fig. 3 the beginning of each action in the sequence cannot be precisely identified from the graph. Even though the participants (healthy people) in the experiment were instructed on how walking with the crutches in each gait pattern, it is necessary to carry out experiments with patients with injuries, to a better understanding of the association among the parameters and the tested patterns.

6 Conclusions and Future Works

One of the primary motivation of this work is the individualization of rehabilitation therapies for gait recovery, through the monitoring of the parameters involved in the gait with crutches. Instrumented crutches for gait monitoring are a convenient tool to know the recovery status of the patient in rehabilitation. This work presented the development of a system to measure the force and the position of the crutch with acceptable accuracy within an indoor environment, and also the results of monitoring four gait patterns. According to data in the table and the graph, it is possible to observe the pre-established sequence for the users and to identify the executed pattern. In this way, therapists could use this data to determine the patient’s performance taking into account the prescribed WB and the pattern. The gait patterns need to match with physical capabilities
and specific characteristics of the user. Further research on this topic will investigate the relation between the WB and each one of the gait patterns and the forces through the affected limbs. Besides, the gait patterns could be classified using the descriptors mentioned above while the user walks with the crutches, ergo online. Future works could investigate too the correlation between gait patterns and injuries or particular conditions. Disabilities affect gait parameters differently. Being the applied force to the crutch is a critical parameter, it is necessary for future experiments to provide a system with biofeedback for the user. So the user will have better learning and understanding of gait patterns during training.

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