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Monitoring healing of orthopedic ailments with an original instrumented crutch

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Abstract

Background. Walking aids are often prescribed in the aftermath of an orthopedic condition of the lower limbs to ensure balance and reduce loading of the injured limb. Correct use of these crutches is difficult because efficient instruments are lacking to monitor the forces acting on the lower limb and crutches.

Aims. The aim of this project was to produce an atraumatic, cheap, and portable tool to assist patients and therapists in rehabilitation, and in conducting gait analysis. With the development of these instrumented crutches, the authors hope to increase their possibilities to monitor the functional evolution of a person during recovery after musculoskeletal ailments.

Methods. We describe the development of a wireless instrumented forearm crutch to monitor the gait of eighteen orthopedic patients during their convalescence. Seven volunteers served as a control group. By using four strain gauges installed as a full Wheatstone bridge, pure compression in the crutch bar is measured. A tri-axial accelerometer is used for determining the movement speed of the crutch in the sagittal plane. The pitch and roll angles in the frontal plane were measured using a tri-axial accelerometer and gyroscope.

Results. Unfortunately, no difference was found between a control group of healthy volunteers and the group of orthopedic patients. Also, the authors did not find a relation between the different gait parameters.

Conclusions. Using the three parameters obtained from the wireless connected forearm crutch, we could not create an algorithm to characterize gait in a group of patients with different orthopedic conditions of the lower leg. The results were not different from the parameters obtained from a group of healthy volunteers.

Keywords: rehabilitation, partial weight bearing, strain gauges, instrumented crutches, real time monitoring, end user program, compression, full Wheatstone bridge.

Introduction

Around six million people in the US are crutch users, and more than 575,000 patients in the USA are prescribed crutches each year (Kaye et al., 2000).

Walking aids are often used as an essential rehabilitation tool to help patients in their functional recovery. Often, the crutch is the last stage in the rehabilitation program after lower limb orthopedic surgery. In addition, much of the time, these patients are somehow reluctant to leave the comfort of a wheelchair. This is not ideal because the use of crutches places the patient in a more physiological upright position (Rasouli & Reed, 2020). Crutches are often difficult to use. Problems such as fatigue and soreness of hands, axillae, and chest wall are often mentioned. Also, the underestimated difficulties patients have when trying to use these crutches without them falling to the ground makes the crutches cumbersome (Merrett et al., 2009; Merrett et al., 2010; Tonutti, 2015).

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Although crutches are often prescribed by a physiotherapist to facilitate postoperative walking, the exact knowledge of the forces acting on the affected limb in a certain clinical situation is difficult to obtain (Rasouli & Reed, 2020; Tonutti, 2015); however, this information is important as instruments used to monitor the progression of functionality and proprioception during rehabilitation are missing. Radiographs provide a lot of information on the healing process. For example, patients often perform poorly on a functional level, even with an excellent radiological outcome. A typical example is total knee arthroplasty, which does not give satisfaction in 20% of the patients. In these cases, radiographs look good, but the patient is lacking functional recovery and has persistent pain and muscle wasting (Kahlenberg et al., 2018).

The aim of this project was to develop an instrumented wireless crutch that records *force, pitch and roll* movement in a plane perpendicular to the line of movement and angle speed of the crutch in a sagittal plane, in line with the patient's progression. Hence, we wanted to increase our armamentarium to monitor gait in an objective way. In part, this work is inspired by previous studies that developed a similar tool (Merrett et al., 2009; Sardini et al., 2014).

Our null hypothesis was to see a clear difference between the control group and the patient group by using force, angle speed of the crutch in the sagittal plane and crutch position as the parameters.

Methods and patients

Between 2015 and 2018 the departments of Biomedical Engineering, Physiotherapy and Orthopedic Surgery of the Free University of Brussels developed a wireless instrumented elbow crutch (Merrett et al., 2009; Sardini et al., 2014; Lofstrand 1948, 1955). In contrast to these previous studies, we were more interested in monitoring the actual loading of the injured limb than the percentage of weight bearing (% PWB). The % PWB indicates the percentage of body weight divided by the crutch and affected limb. Although partial weight bearing is commonly used as a guide in postoperative rehabilitation, % PWB is rather ambiguous. The current subjective method asks the patient to rest on the weight scale to evaluate what the target PWB feels like. Patients are unable to follow prescribed instructions on how much to load the affected limb. In our setting, with real load recording, no audible biofeedback was needed. In total, we gathered 18 patients and seven volunteers for the current pilot study.

Design of the instrumented crutch. The crutch in the current study is a standard elbow crutch with an aluminum frame. The advantage of using these crutches has been previously described (Papadosifos, 2014; Rasouli & Reed, 2020). Therefore, an aluminum crutch was the optimal choice, because of its lightness (2,700 kg/m^3), tensile strength (70-700 MPa) and Young's modulus (69 GPa) (***, 2015).

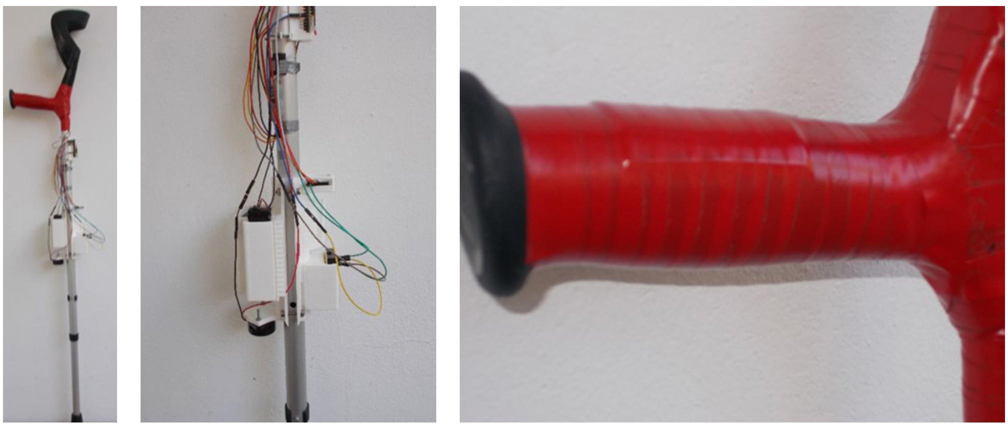
The prototype includes four strain gauges installed as a full Wheatstone bridge. Pure compression in the crutch bar is measured. In addition, a gyroscope and a tri-axial accelerometer (GY-521) are used to compute the roll and pitch angle. Lastly, the data is sent by Bluetooth to a developed end user program made in Python by means of a microcontroller (ESP32) (Fig. 1).

Data can then be visualized simultaneously on a computer, or retrieved at a later time. These data could give the examiner an idea of the cadence (smoothness) of walking expressed as periods in time.

The gyroscope was used to calculate the position of the crutch in relation to the center of the body in the frontal plane. In theory, leaning away from the neutral axis of the body could bring a higher load on the crutch and a lower load on the contralateral leg (Fig. 2a, b).

We made an assumption that, with the Lofstrand crutch, the torque, because of the eccentric loading of the crutch, would be minimal due to the resting position of the forearm, seated well in the forearm cuff of the crutch (Brinckmann et al., 2016).

A summary of component choices for the instrumented crutch is presented in Table I.



a) b) c)

Fig. 1 – Instrumented crutch.

Fig. 2a – Crutch position: negative

Fig. 2b – Crutch position: positive

Table I

A summary of component choices for the instrumented crutch.

Purpose	Component
Microcontroller & Interface	Arduino Uno
Pitch sensing	MPU-6050 Gyroscope/ Accelerometer IMU
Wireless transmission	ESP32 LoRa
Off/On Switch	Rocker Switch
Graphic Software	PyCharm version 2019.1.3 (Jet Brains Czech)

Patients used for the study

All patients gave their informed consent to participate in the study.

A feasibility study was conducted with 18 patients who displayed different orthopedic ailments. Also, seven normal volunteers (three females and four males) were included in the current pilot study as controls. Patients with neurological problems and elderly with dementia who were not able to understand the purpose of the study were excluded from participation. We chose a two-point contact contralateral crutch gait because this type of support is mostly prescribed at the end of the revalidation period of an orthopedic ailment.

The main objective of the current study was the feasibility or handling of the instrumented crutches. In addition, we wanted to characterize the quality of walking, which was taken into account using the three parameters obtained from the crutch: angular speed of the crutch in the sagittal plane, expressed as cycles per second (Hz), force (Newton) and crutch position (index).

The position of the crutch was represented by a curve with positive and negative parts. The positive and negative areas under the curve were calculated and presented as an index; the positive area divided by the negative area.

An index above 1 means the crutch was leaning away from the body center, and that patients were putting more pressure on the crutch. An index of less than 1 means the crutch was kept closer to the midline of the body, with more pressure on the contralateral limb.

The crutch position index is the ratio between the positive area and the negative area of the recorded curve (Fig. 3).

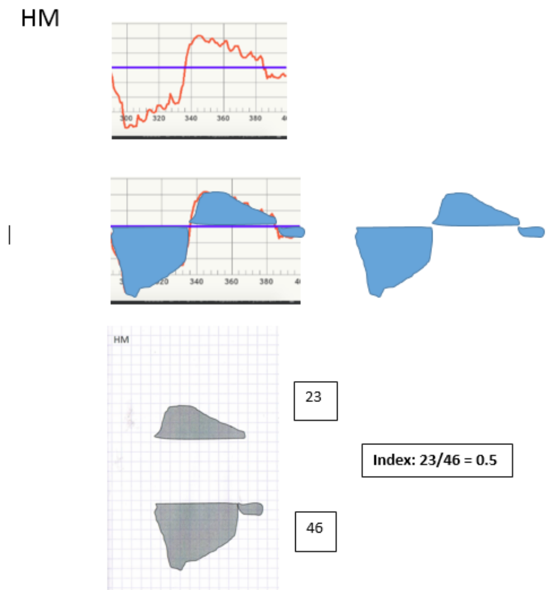


Fig. 3 – Measuring the area under the curve for positioning of the crutch in the frontal plane.

Data of the patients were compared with data from the volunteers (Table I).

The load on the affected leg was calibrated with a mechanical scale, and this was repeated before every recording (Fig. 4).

Fig. 4 – Callibration of the crutch before each test was done with a bathroom scale. The crutch was positioned on wooden blocks to be level with the mechanical scale.

The patients and volunteers were asked to practice with regular crutches for 15 minutes. After that, they were asked to walk in bare feet across an indoor trajectory three times over a distance of 5 meters with the instrumented crutches; this was done on a non-slip conductive rubber walkway. The test was repeated five times for every crutch position.

The data, force, frequency and crutch positions were recorded by a portable computer with Bluetooth capabilities (Fig. 5).

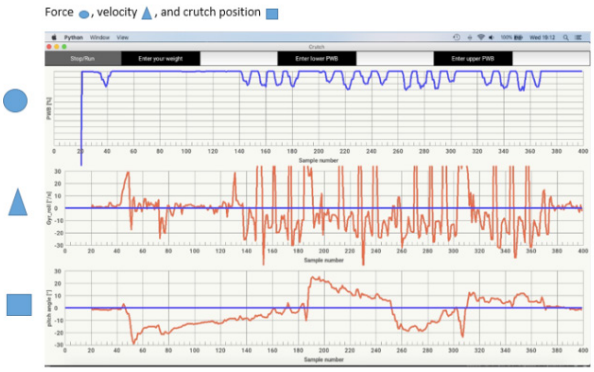


Fig. 5 – Example of data acquired from the instrumented crutch.

Statistics

GraphPad Instat 3 was used. The statistical analyses assessed the Gaussian distribution by using the Kolmogorov–Smirnov test. An unpaired non-parametric Mann-Whitney test was used to compare the means. Regression and correlation were tested with multiple X variables (multiple regression). The level of significance was set at 5%.

Results

In two cases, we could not record the data for technical reasons. For these reasons, one volunteer and one patient were excluded.

a) A multiple regression analysis between the *force as a constant* variable with frequency and position of the crutch (pitch) within the *group of volunteers* is as follows:

- Force = 32.529 +6.187xV- 0.4981xPitch
- R^2= 2.24% percent of the variance in force explained by the model.
- P value is 0.8533 and is considered not significant.
- Looking for the significant contribution of one variable, we could not find a variable that contributed to the results significantly.

b) The multiple regression analysis between *force as a constant* variable with frequency and position of the crutch (pitch) within the *group of patients* is as follows:

- Force= 87.677- 0.8762xV-0.3186xPitch
- R^2=2.84% percent of the variance in force explained by the model.
- *P value is 0.7609*, which is considered not significant.
- Looking for the significant contribution of one variable, we found force as a variable that contributes significantly to the equation.

c) A non-parametric Mann-Whitney test was performed to compare the variable *force* between volunteers and patients. The two-tailed *P value is 0.1197*, which is considered not significant.

d) A non-parametric Mann-Whitney test was performed to compare the variable *frequency* between volunteers and patients. The two-tailed *P value is 0.7233*, which is considered not significant.

e) A non-parametric Mann-Whitney test was performed to compare the variable *pitch* between volunteers and patients. The two-tailed *P value is 0.4509*, which is considered not significant.

Discussion

This is the first study where an instrumented crutch was used to monitor the walking gait of patients, using healthy subjects as the control group. Other studies have merely used healthy subjects (Merrett et al., 2009; Sardini et al., 2014). Very few articles exist on the subject of instrumented crutches. Sometimes, these are also called “intelligent crutches” (Merrett et al., 2009; Sardini et al., 2014; Tonutti 2015).

Interestingly, previous scholars recorded the loading as a percent of the total load bearing capacity of a limb (Stallard et al., 1980). The % PWB is often used to indicate how much weight a patient can bear. In reality, this has little value. In contrast to some authors who stated that overdue weight bearing on the injured leg was possible (Aro & Chao, 1993), it was never proven that normal patients, without severe proprioceptive deficits, were able to overload and damage healing limbs. Also, the notion of % PWB is exceedingly difficult to use as a communication tool with physiotherapists. Overall, patients do not understand what it means to load the injured limb to a certain percentage.

Therefore, we adopted another strategy in our pilot study: the real loading of the injured limb was measured.

In combining this new strategy with angular frequency of the crutch movement in the sagittal plane and positioning of the crutch in the frontal plane, we hoped to create an algorithm that could characterize the quality of walking. With this algorithm we could express, in percentage, the progress in recovery from an orthopedic ailment of the lower limb.

Unfortunately, we could not find any significant difference between patients and volunteers for all three studied parameters: *force, angle speed of the crutch in the sagittal plane* and *crutch position*. Also, a multiple regression analysis could not give a clear explanation of the variance between the other variables.

Our results do not corroborate with the findings of Smidt and Mommens who showed in their study that normal gait is faster than walking with crutches (Smidt & Mommens, 1980). Also energy consumption, which is the area under the force versus velocity curve, did not show any differences between patients and the control group. In other studies, the indoor track also included stair climbing indicating a variation in difficulties (Merrett et al., 2009; Merrett et al., 2010; Tonutti, 2015; Sardini et al., 2014; Stallard et al., 1980).

In our study, the walking pad was smooth, without any obstacles, making walking easy, too easy?

Although the results are rather disappointing, it is worth noting that:

a) For a healthy volunteer who has no knowledge of crutch handling, it seems rather difficult to learn this. In most other studies, only healthy subjects were used. This makes their results difficult to compare with the results of the current study, where patients were predominantly investigated.

b) As we can see from the position of the crutch, this varied from patient to patient. In the recorded curve of a same patient, the position of the crutch could be both positive (upper part of the crutch away from the axis of the patient) and negative (upper part of the crutch near to the axis of the patient). The index values varied from 0.01 to 79.

c) The knowledge of loads and inclinations of the crutch can provide valuable information for walking correctly. The recorded data can be used for a variety of applications. The previous instrumented crutches were merely developed with an audible biofeedback system that warned the patient when he or she was overloading his or her limbs. The cut-off point for overloading the injured limb is an intuitive process made by the physiotherapist and is merely based on his opinion as an expert (level V of evidence). As previously mentioned, the patients seemed unable to follow the prescribed instructions on how much load to place on the affected limb.

We would like to acknowledge some shortcomings of the study as well.

A major drawback was the fixed length of the crutch. Because of the applied equipment of the inbuilt sensors, adapting the length of the crutch to the patient length was difficult. As a general guideline, the length of the crutch should be approximately 75% of patient's height (Kendall et al., 2005).

Because of the insufficient packaging of the hardware around the crutch, the wired crutch became fragile and difficult to use outside the laboratory.

The reason for not finding a cluster of data that could be used to characterize gait progress in patients is not straightforward and represents a rather counter-intuitive observation. Obviously, characterizing walking with only three parameters looks futile. Probably, more variables play an important role in walking with a crutch. For example, the damping of loading by proprioception and muscle action could not be incorporated in our model.

Conclusions

1. We constructed an instrumented crutch that could record the actual loading of the limbs together with the angle velocity of the crutch in the sagittal plane and position of the crutch in the frontal plane.

2. Unfortunately, with the data recorded, we failed to obtain a significant algorithm that could be used to evaluate the progress of the patient while recovering from an orthopedic ailment. Regarding the above mentioned analyses and results, we have to reject our null hypothesis.

Conflicts of interests

The authors declare to have no conflict of interest in the above mentioned article.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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