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An instrumented crutch for monitoring patients' weight distribution during orthopaedic rehabilitation

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Abstract

This paper discusses an instrumented forearm crutch that has been developed to monitor a patient's weight bearing over the full period of their recovery, and that can potentially be used in a home environment. The crutch measures the applied weight, crutch tilt, and hand position on the grip. Data are transmitted wirelessly to a remote computer, where they are processed and visualized in LabVIEW. The results obtained from a successful pilot study highlight both the need for such an instrumented crutch and its ability to measure the weight being applied through a patient's lower limb.

Keywords: assistive healthcare; forearm crutches; instrumented objects; biomedical engineering

1. Introduction

Forearm crutches are used routinely following certain lower limb operations to reduce weight-bearing through the affected limb and optimize the healing conditions for bone and soft tissues. It is widely recognized that excessive loading of the lower limb following certain types of surgery can disrupt the operated tissues and put the healing bones at risk of mal-union. It has also been recognized that prolonged unloading of the articular cartilage causes the cartilage to become less stiff and less able to tolerate high loads, suggesting a need for a program of graduated weight-bearing and activity following extended periods of non-weight-bearing[1]. In order to load the affected limb to an appropriate level (not too excessive or too moderate for the particular case), a patient receives instruction from their physiotherapist to apply a certain fraction of their body weight through the crutch axis as they walk. If these instructions are not followed, incorrect weight-bearing can potentially increase the rehabilitation period and risk further and long-term damage to the affected lower limb. Instructing patients on partial weight-bearing is a difficult task for the physiotherapist as there is currently no objective way of being able to measure exactly how much weight is being applied through the leg. A patient's perception of the loading on their leg is often prone to considerable error and clinicians can give only subjective verbal feedback and instruction to the patient as a result of a visual inspection.

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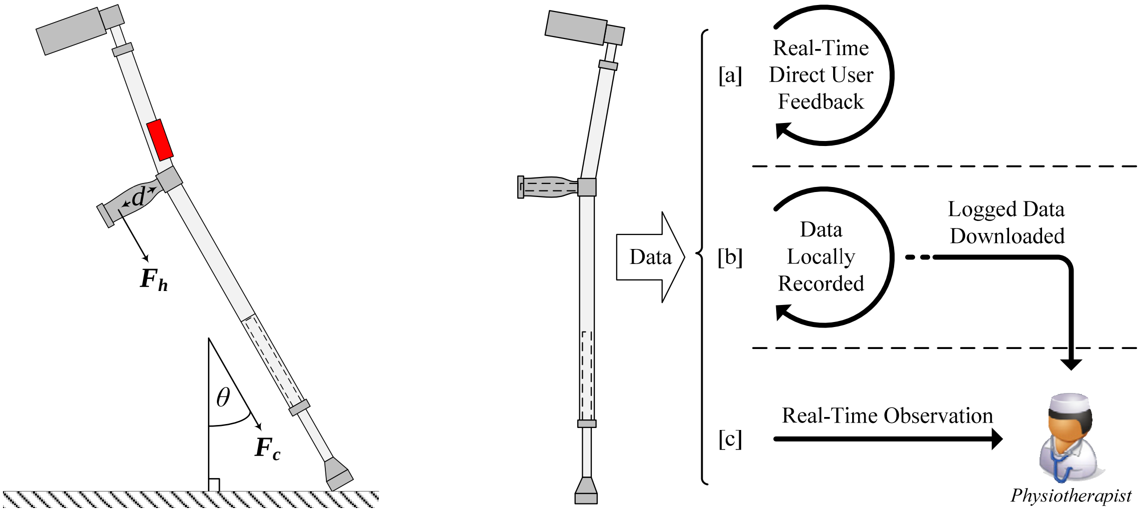
This paper discusses the development of an instrumented crutch to monitor the force being applied through its axis in order to obtain an objective estimation of the weight being exerted through the affected limb over the full period of recovery (including its potential use in the home environment). This provides the clinician with vital information in teaching patients how to correctly use the crutches, and is essential when weight-bearing is limited by surgery or injury. To assist in teaching patients the correct usage of forearm crutches, the tilt of the crutch and position of the hand on the grip are also measured.

The concept of an instrumented walking aid has been previously investigated by Wu et al.[2], where a ‘smart cane’ for geriatrics was developed to monitor the usage of the cane and infer further information about the patient’s well-being. For example, accelerometers identified when the cane was dropped or if the patient had fallen. The requirements for an instrumented crutch are largely distinct from this as, unlike the ‘smart cane’ which is used to assist full-weight-bearing gait only, the crutch is used to reduce and control the loading on the lower-limb following an injury. While earlier research has developed instrumented crutches for analyzing kinematics and usage within a laboratory environment[3], our proposed device is intended to be used for assistive healthcare (i.e. used for the full period of a patient’s rehabilitation programme) and, as such, has not been previously investigated.

2. Design of an Instrumented Crutch

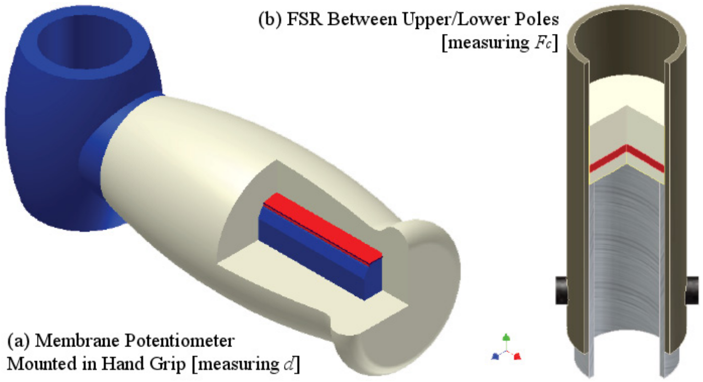
Through consultation with physiotherapists at Southampton General Hospital, it was decided that the primary aim of the proposed system would be to monitor the magnitude of the force translated through the axis of the crutch ($|\boldsymbol{F_c}|$ in Fig. 1a) thus allowing the weight-bearing of the injured limb to be estimated. The secondary aims of the system include measurement of the tilt of the crutch (the angles between the crutch and the ground parallel and perpendicular to the walking direction, i.e. the roll and pitch components of the unit vector $\widehat{\boldsymbol{F_c}}$), and the position ($d$) at which the grip force (F_h) is applied to the handle.

Fig. 1b shows some of the potential uses of the instrumented crutch including real-time observation by the clinician (to train patients how to use the crutch), local logging of data for offline analysis by the clinician (allowing long term monitoring in order to analyze home use of the crutches), and to provide real-time feedback to the patient (encouraging them to consistently put the recommended weight through the affected limb). The developed crutch (Fig. 2b) currently implements only real-time observation. A microcontroller on the crutch samples the sensors and transmits data wirelessly to a remote computer, where it is processed and displayed in LabVIEW (Fig. 3a).



(a) (b)

Fig. 1. (a) The forces, angles, and distances sensed by the instrumented crutch; (b) Conceived uses of the instrumented crutch (only [c] is currently implemented).



(a) *(b)*

Fig. 2. (a) The locations of the sensors inside the i) hand grip, and ii) main crutch pole; (b) the instrumented crutch showing the locations of the energy source, sensors and cabling .

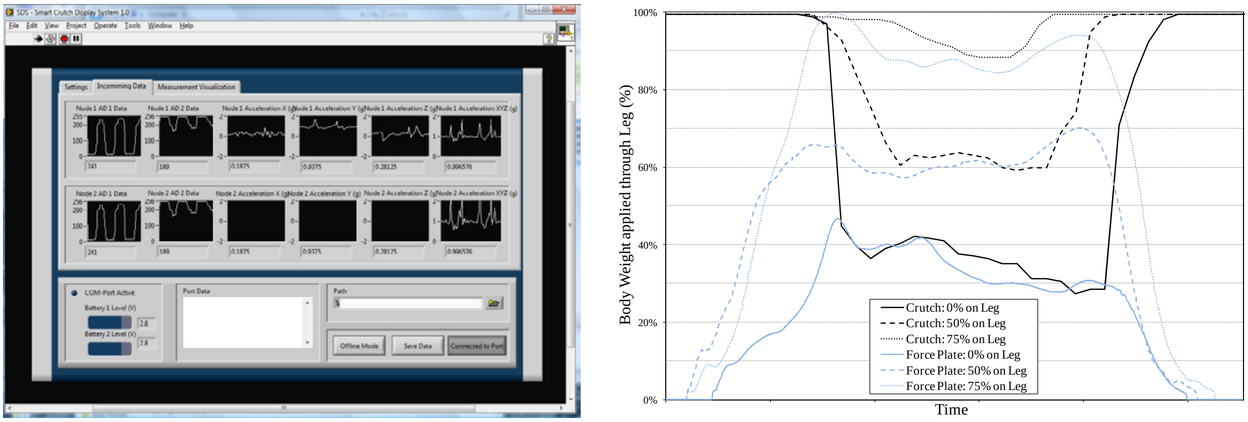
The magnitude of the force down the axis of the crutch, $|\boldsymbol{F_c}|$, is measured using a FlexiForce® Force Sensitive Resistor[4] (FSR) mounted inside the crutch pole (the location of which is shown in Fig. 2). The FSR was conditioned assuming a maximum force of 1kN (equivalent to a patient's weight of ≈100kg) and the force-resistance relationship was characterized over this range with a relative error of ≤10%. Equation (1) is used to calculate the percentage of the patient's body weight that is translated through their affected leg from $|\boldsymbol{F_c}|$, where M is the mass of the patient (kg) and g is the acceleration due to gravity (ms^{-2}). Note, equation (1) is only true for the case where a single crutch is used, and at the point in the patient's gait cycle where their complete weight is applied through either their affected leg or the crutch.

$$W_{\%} = 1 - |\boldsymbol{F_c}|/(M \cdot g) \tag{1}$$

The crutch tilt, $\widehat{\boldsymbol{F}}_{\boldsymbol{c}}$, is measured using a tri-axial accelerometer and calculated with the assumption that dynamic accelerations (accelerations not due to gravity) are negligible. Finally, the distance at which the grip force is applied to the handle, d, is measured using a membrane potentiometer mounted inside the hand grip (the location of which is shown in Fig. 2).

3. Results

A small pilot study was performed to evaluate the system and to assess the potential for using a single instrumented crutch to estimate the weight-bearing through a limb. The study recorded the magnitude of the force translated through the axis of the instrumented crutch in addition to the magnitudes of the force vectors from two Kistler force plates (positioned alongside one another). The healthy subjects were given the instrumented crutch to use with their right arm (i.e. the right leg is the 'affected' leg) and instructed to walk across the force plates with their right leg coming into contact with one, and the crutch with the other. They were asked to do this three times, attempting to put 0%, 50% and 75% of their body weight through the affected leg.



(a) *(b)*

Fig. 3. (a) The LabVIEW interface showing the raw sensor data obtained from the crutches and the battery levels; (b) The percentage of the subject's body weight that was put through their 'affected' leg during a step on the force plates.

The data obtained from the instrumented crutch and the force plates for one subject is shown in Fig. 3b. First, it can be observed that there is a good correlation between the data obtained from the force plate and the data obtained from the instrumented crutch. The reason that the 'crutch' data returns to 100% of body weight through the affected leg before and after the step is an artifact caused by equation (1); if the crutch is not in contact with the ground (hence $|\boldsymbol{F_c}| = 0$), it is assumed that all of the patient's body weight is being applied through their affected leg (in fact, their other leg is bearing all of their weight). This is not evident when the force plates are used, as the patient's other leg is not in contact with the force plate. Second, the inability of the subject to correctly apply 0%, 50% or 75% through their affected limb can be seen (a maximum error of approximately 40%, 15% and 20% respectively). This highlights the requirement for better monitoring of the patient's rehabilitation.

4. Conclusions and Future Work

This paper has presented an instrumented crutch for the monitoring of weight-bearing during orthopaedic rehabilitation. The preliminary results that have been obtained from the crutch show that the weight-bearing of the patient can be estimated from only one crutch. Further studies will investigate the use of two instrumented crutches for better estimation of weight-bearing and make the device more clinically relevant and appropriate for use during patient rehabilitation. Further, integration of the local feedback and storage mechanisms identified in Fig. 1b are required in order to influence and monitor patient behavior and to locally record data for subsequent offline processing. More complex data-processing (both on-board and on-computer) will be required to analyze and fuse sensor data (in particular to identify the maximum force put through each leg), and a more comprehensive study will be performed in order to evaluate the system.

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