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Biomechanics in crutch assisted walking

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ABSTRACT
Crutch-assisted walking is very common among patients with a temporary or permanent impairment affecting lower limb biomechanics. Correct crutches' handling is the way to avoid undesired side effects in lower limbs recovery or, in chronic users, upper limbs joints diseases. Active exoskeletons for spinal cord injured patients are commonly crutch assisted. In such cases, in which upper limbs must be preserved, specific training in crutch use is mandatory. A walking test setup was prepared to monitor healthy volunteers during crunch use as a first step. Measurements were performed by using both a motion capture system and instrumented crutches measuring load distribution. In this paper, we present preliminary tests results based on different subjects - having a variety of anthropometrical characteristics - during walking with parallel or alternate crutches, the so-called three and two-points strategies. Tests results present inter and intra subject variabilities and, as a first goal, influencing factors affecting crutch loads have been identified. In the future we aim to address crutch use errors that could lead to delayed recovery or upper limbs suffering in patients, giving valuable information to physicians and therapists to improve user's training.

Section: RESEARCH PAPER

Keywords: Biomechanical measurements; crutches; articular loads; force measurements

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1. INTRODUCTION

Different diseases may require patients to use crutches in their daily life. While upper limbs fatigue is limited when a temporary impairment is considered, it may become an important issue when considering permanent impairments such as those due to stroke or multiple sclerosis. These situations are rather common and important in today's society. Stroke is the leading cause of movement disability in the USA and Europe [1]. People who suffer a stroke experience change in strength, muscle tone, and neuromuscular coordination [2], the consequence of which are mobility, balance, and walking disabilities [3]. Similar symptoms are present in multiple sclerosis, along with fatigue and cerebellar involvement. Up to 10% of adults suffer from reduced mobility because of conditions such as a central nervous system lesion that affects balance and gait. On the other hand, walking is a fundamental human activity [4] and if impaired, people prioritize it as a goal of treatment [5]. In Europe walking aids, such as crutches, are the most prescribed tools in case of central nervous system lesions [6] and, in a gait rehabilitative framework, physical therapists guide patients in using crutches to better support weight by reducing the magnitude of the load on the legs, and to improve balance by increasing the body's base of support [7]. Moreover, crutches use is fundamental for people walking with the assistance of exoskeletons, for example after a Spinal Cord Injury (SCI). Exoskeletons help in closing the gap toward a normal life for SCI people. Since, generally speaking, exoskeletons require the contemporary presence of a pair of crutches, their continuous and daily usage requires attention to possible consequences such as shoulder pain [8].

On this basis, a pair of instrumented crutches was developed to measure both crutch load and orientation [8]-[9], and they were integrated with an optoelectronic motion capture system, an anthropometric volume scanner, and a biomechanical model, in the Bullet project [10]-[11].

Figure 1 depicts Bullet main concept. Bullet biomechanical model is fed with kinematic data describing trajectories and accelerations [12], and crutch force data describing movement dynamics. Eventually ground reaction forces under the feet can

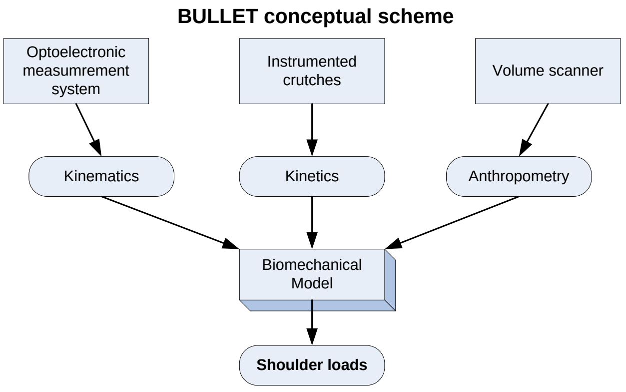

Figure 1. Bullet conceptual scheme.

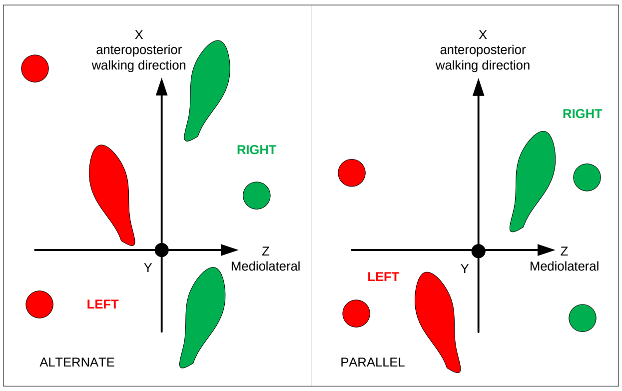

Figure 2. Alternate and parallel gait strategies.

be included to operate the model in its complete, full body version.

To obtain upper limbs loads the model requires subject's anthropometry also. To obtain such segment detailed information generally we refer to anthropometric tables, where values relative to overall subject mass and height are reported [13]-[14]. To compensate for the consistent subject to subject differences , that are common among exoskeleton users, Bullet includes a Volume scanner to measure segments volumes using a Kinect Azure camera [15]-[16]. The scanner considers a set of subject images recorded in both RGB and ToF frames, and a segmentation software based on the biomechanical model definition to obtain segments volumes. Segments masses and inertia are then determined considering segment's density values as reported in tables and literature [14].

Bullet biomechanical model, process the input data to obtain limbs loads with special attention to torques at shoulders [17]. The focus, in this case, is related to Exoskeletons assisted walking in the Eurobench project framework [11], but the approach is general [18] and, in this paper, some preliminary results are presented for healthy subjects walking with crutches without exoskeletons. The main goal is to investigate differences in crutch-assisted gait following the three points strategy - or parallel crutch use – and the two points strategy – or alternate crutch movement. Therefore, some results regarding crutch kinematics and loads for the two strategies are here presented.

2. EXPERIMENTAL SETUP AND PROTOCOL

The experimental setup includes an optoelectronic motion capture system, to reconstruct the full-body and crutches kinematics during gait, two force plates for measuring the ground reaction forces under the left-right foot – both from BTS Bioengineering, Milan, Italy –, and a pair of instrumented crutches to measure force load and orientation on each side, as described in [9]. Calibration procedures have been applied for both optoelectronic and force measurement systems [18] before each subject test session. In the following, special attention will be given crutches kinematics obtained from optoelectronic systems and related crutches forces.

The experimental protocol requires placing a set of 39 markers on specific subjects' landmarks, plus three on each crutch. In this experimentation heathy subjects only are involved. Since they have to use crutches simulating a Spinal Cord Injury walking impairment, they trained for a short time before test. To this purpose subjects consider to have problems to move and load both legs, so a pre-training is required to establish a proper crutch load and movement, according to experimenter's instructions. Moreover during the training subjects find the proper path and foot sequence in the corridor, to place feet properly on force plates without crutch interference. During the training and the following tests there is no real time control on crutch load, so, at the end, it depends on subject voluntary behaviour. Then, after performing calibration procedures for all the instruments, three repetitions (minimum) for each walking condition were carried out: three points gait with parallel crutches and two points gait with alternate crutches, as shown in Figure 2. A set of 14 subjects - of which 2 females, mean age 25.7 years, standard dev. 5.6 years - undergo the experimental protocol, after signing an informed consensus agreement. Finally, 124 valid tests were obtained, 65 of which in the two-points (alternate) gate conditions.

3. EXPERIMENTAL RESULTS

Biomechanical model can operate in complete – whole body – or partial – upper limbs only – mode. In the following we consider the whole body version that includes 18 segments to

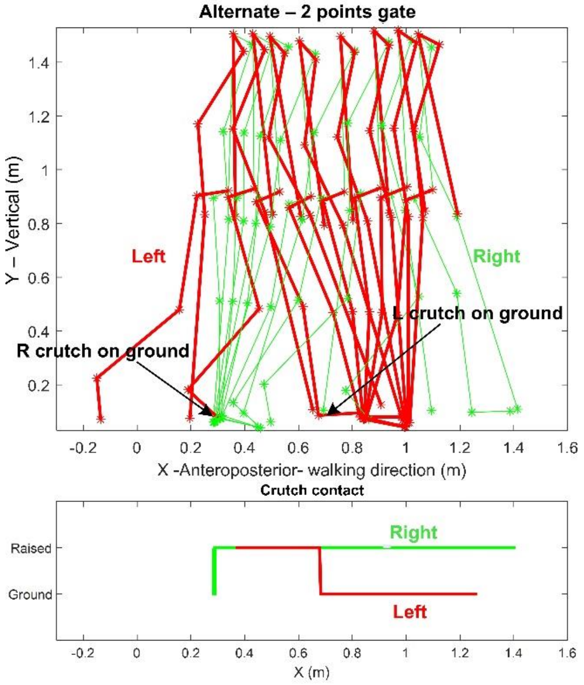

Figure 3. Alternate and parallel gait strategies.

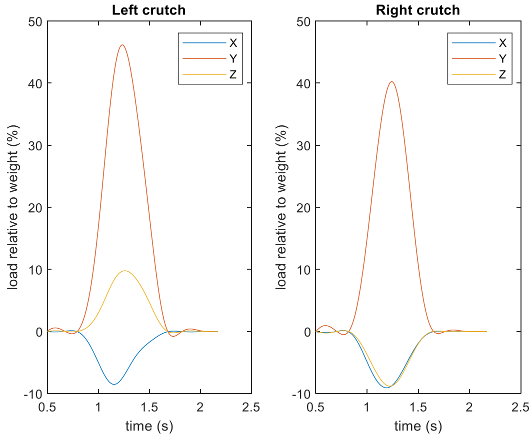

Figure 4. L/R crutch relative forces in the three directions: parallel gait.

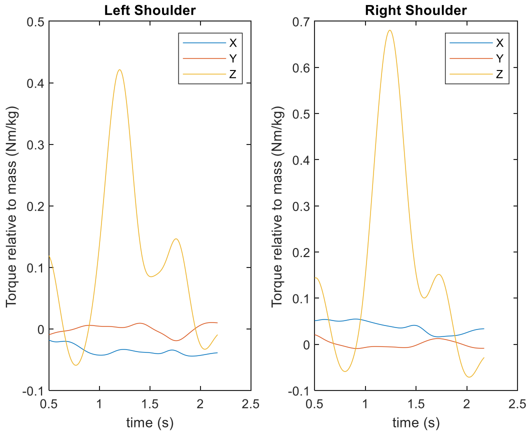

Figure 6. L/R shoulder torques for parallel gait.

describe subject and crutches movement as shown in Figure 3 for an alternate – two points - gait.

Figure 4 presents an example of the three crutch force components according to the biomechanical reference systems indicated in Figure 2 – X anteroposterior, Y vertical, Z mediolateral – for a three-point gait and left-right sides.

By using force measurement it is possible to define the crutch contact on the ground –Figure 3 lower graph- and consequently identify initial and final contact angles on the two most important planes describing the movement: the sagittal (X, Y) and the frontal (Z, Y) ones. Besides that, it is possible to compute the angular crutch range of motion (ROM), maximum, and rms load force during crutch ground contact. Since data recording was limited to few gaits near and on the force plates, we have excluded from these computations the runs in which some data was missing: for example, when no initial or final crutch ground contact was recorded, and consequently it was not possible to evaluate parameters on a complete contact phase. In the following all the trained subjects are considered independently of their ability to simulate the impairment.

Results from the 124 valid tests are summed up in Table 1 as regards mean values and relative standard deviations of the maximum crutches forces normalised by subjects' weight. Note that variability includes inter subject repeatability and intra subject variability.

The large relative standard deviation suggests that, besides subject behaviour, other differences are present. For example, gait condition might affect crutch loading. Moreover, even if results are normalised for subject's weight, other anthropometric differences might have an important role in crutch load.

On this basis the biomechanical model can evaluate shoulders torque. Figure 5 and Figure 6 presents L/R shoulder forces and torques in relation with crutch contact for a parallel gait.

It is worth noting that the model we are considering is purely mechanical, so muscles action is summed up in the torque at shoulders joints, while forces do not include reactions due to muscle actions applied at tendon insertion points. Even if this is certainly an approximation, the proposed approach is free from any assumption regarding tendon anthropometry and muscle force behaviour that in our specific case could be critical, since we are considering injured subjects walking with crutches.

Table 1. Maximum crutch vertical load: results summary

	Right		Left	
	Mean (% of sbj weight)	**Relative standard deviation**	**Mean (% of sbj weight)**	**Relative standard deviation**
Parallel	30	32 %	34	30 %
Alternate	21	43 %	24	40 %

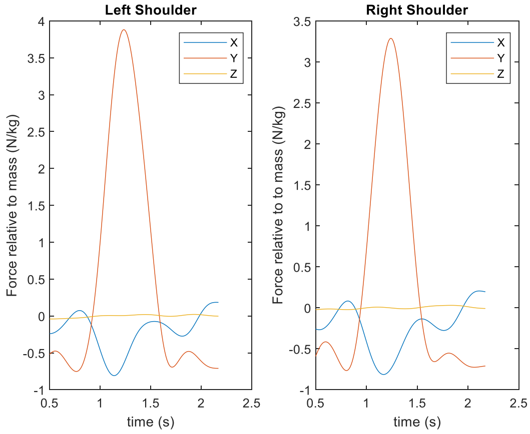

Figure 5. L/R shoulder forces for parallel gait.

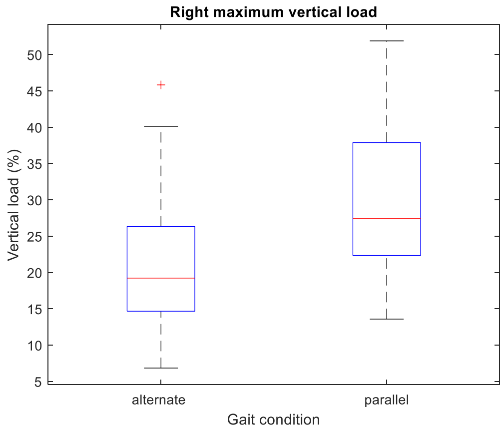

Figure 7. R crutch vertical maximum relative forces for alternate/ parallel movement. Boxes represent 25%-75% intervals, red lines median values.

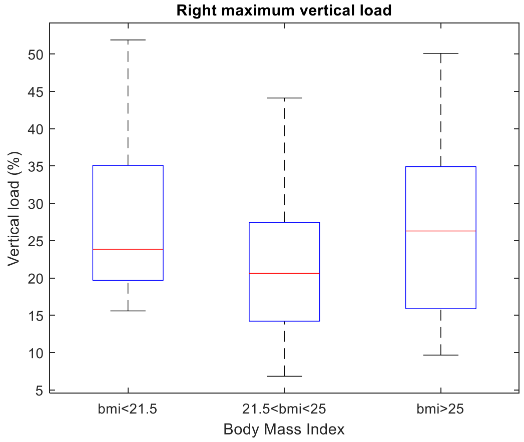

Figure 8. R crutch vertical maximum relative forces for the three BMI categories. Boxes represent 25%-75% intervals, red lines median values.

4. DISCUSSION

As mentioned in the introduction the focus here is on two crutch use modalities and on the percentage of the subject weight that is moved from the lower limbs toward the crutches. As shown in Figure 4 main load behaviour is very similar for left/right crutches, while the mediolateral component (Z, orange in Figure 4) is opposed due to the opposed crutch contact angle in the medio lateral plane.

The overall data set can be divided according to these two gait conditions – parallel/alternate, and since we have several repetitions (about 3) for a rather consistent set of subjects (18), we can make a multiple-way analysis of variance.

The analysed variable can be selected among the available gait parameters we have measured. We can consider a crutch centred approach considering both crutch kinematics and dynamics, or a subject centred approach considering shoulder internal loads in relation with gait behaviour.

As an example of the first approach we consider maximum and rms vertical load relative to the subject's overall weight. As factors for the analysis, besides the mentioned gait conditions, we consider kinematics parameters, such as the angular ROM of the crutch around the medio-lateral axis, and subject anthropometric characteristics such as weight, height, or the Body Mass Index (BMI), defined as the ratio between mass and squared height. In Table 2 we present an example of ANOVA results, including *F* values. Considering the maximum vertical load on the right and left crutches, *F* values confirm that the gait condition is significant with a probability $< 10^{-4}$. The box plot in Figure 7 shows an evident gait strategy effect on load levels. There is also evidence of a large variability, probably due to the protocol that requires to simulate an impairment – see paragraph 2 - and the absence of an online verification of such imposed behaviour.

Table 2. ANOVA results for L/R crutch rms vertical load.

	Mean Squares	F value	Probability>F
Moving condition	3.7	25.3	0
Subj BMI	5.3	18.1	0
Subj Mass	1.9	6.5	$2\ 10^{-3}$
Subj Height	0.2	0.7	0.49
Crutch ROM	2.1	2.9	$1.5\ 10^{-2}$
Residual error	31	-	-

Moreover, there is evidence that, even if working with a load normalized on subject weight, the subject's BMI is significative $(p < 10^{-4})$ indicating that the way crutches are loaded is not simply related to the subject's mass.

However, the box plot in Figure 8 shows a less evident load dependency on the three BMI categories, defined as follows: $BMI < 21.5\ \mathrm{kg/m^2}$, $21.5\ \mathrm{kg/m^2} \leq BMI < 25\ \mathrm{kg/m^2}$ and $BMI \geq 25\ \mathrm{kg/m^2}$. This aspect deserves some attention in future data analysis to investigate the most significant subject anthropometric characteristic.

These results have effect on shoulders loads obtained from the biomechanical model. As shown in Figure 6 torque time behaviour is similar for right/left limbs, and present the maximum value, as expected, for torque around the medio lateral axis (Z). On this basis a good example is the analysis of variance of shoulder maximum Z torque. Alternate/parallel walking condition and BMI still have the main effect on this shoulder torque $(p < 10^{-4})$, as shown in the boxplot in Figure 9 for walking condition. While subject's BMI is significative as for crutch loads, other anthropometric characteristics are not significative anymore at the 5% probability level Fisher test, as confirmed by the boxplot in Figure 10 for subject's height.

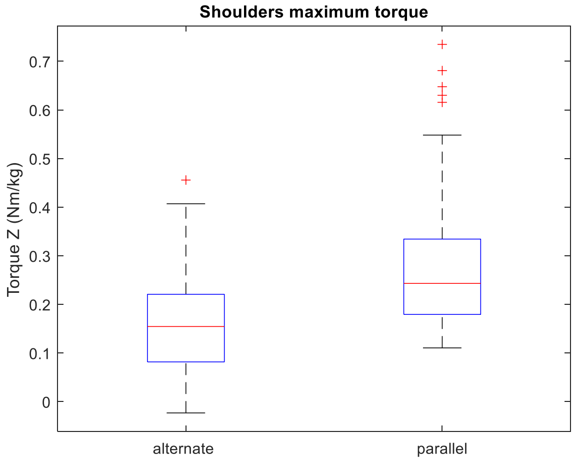

Figure 9. L and R shoulders maximum torque around the mediolateral axis Z for the two walking conditions. Boxes represent 25%-75% intervals, red lines median values.

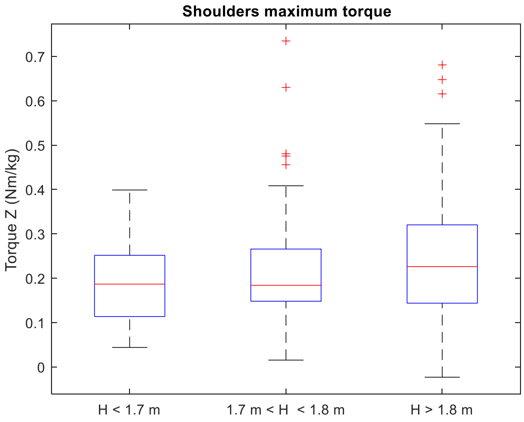

Figure 10. L and R shoulders maximum torque around the mediolateral axis Z in function of subject height categories. Boxes represent 25%-75% intervals, red lines median values.

5. CONCLUSIONS

The paper has presented the Bullet project approach to shoulders load evaluation when walking with crutches. A set of experimental data obtained on healthy subjects has been considered to demonstrate the potentialities of the proposed approach. A preliminary synthesis on these results, is obtained applying the analysis of variance. ANOVA has shown that parallel or alternate walking conditions is very important as regards both crutch forces, that can be measured directly, and shoulders loads, that are determined through a biomechanical model. Subjects' anthropometric characteristics affects results even if they are normalized by subject mass or weight, moreover subjects' BMI is not the only significative parameter since still mass has a significative contribution. Of course such considerations have to be limited to this specific experimentation, since it was conducted on healthy subjects only, with a request to simulate a SCI walking impairment, and subject behaviour was not subject to control. Nevertheless results demonstrate the potentialities of the presented approach. In particular, when applied to injured subjects, it provides a set of information that will be useful to therapist and subjects to improve their training preserving articulations' health.

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