

Biomechanical study on axillary crutches during single-leg swing-through gait

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Abstract

This paper describes a kinetic and kinematic study on axillary crutches during one-leg swing-through gait. The primary objective is to evaluate the interplay of forces at the crutch and body interfaces and to relate them in the understanding of problems associated with the use of axillary crutches. Ten normal adult male subjects with simulated left leg impairment participated in the study. For data acquisition, the VICON kinematic system, a Kistler force plate and an instrumented crutch (with force transducers at the two upper struts close to the axillary bar and one near the crutch tip) were used. Results showed that the peak ground reaction force on the weight-bearing leg during lower limb stance increased by 21.6 percent bodyweight. The peak reaction force transmitted to the arm during crutch stance was 44.4 percent bodyweight. These increased loadings could be detrimental to patients with unsound weight-bearing leg and upper extremities respectively. When the crutches were used incorrectly, 34 percent bodyweight was carried by the underarm. This could cause undue pressure over the neurovascular structures at the axillary region.

Introduction

Axillary crutches are widely used either temporarily or permanently to assist ambulation in various type of locomotor disabilities. They are used for relieving weight-bearing on operated or injured lower limbs and also in some cases of lower limb paralysis for the purpose of ambulation.

The use of axillary crutches however is not without problems. Brooks and Fowler (1964) had reported complications such as axillary

artery thrombosis. Rudin and Levine (1951) had observed the compression of the radial nerve by the axillary bar. Jebsen (1967) noted that though sensation is rarely affected by radial nerve compression, motor weakness may become subtly worse. He warned that this may lead to complete paralysis of the triceps and forearm extensor muscles. These adverse effects are usually a result of bearing weight directly on the axillary bar under the arm during crutch walking.

Several papers have been published on various biomechanical aspects concerning the use of axillary crutches. Shoup et al (1974) reported on the kinematics of swing-through gait with both feet landing using axillary crutches. Four normal adult male subjects were used in their study. They recommended three possible design improvement criteria : (a) to minimize the vertical motion of the upper body; (b) to minimize the shock associated with planting of the crutch tips; and (c) to minimize the need for lateral motion of the crutch tips. Stallard et al (1978) observed that during swing-through gait with axillary crutches, the vertical ground-foot reaction forces increased by 24.5 percent bodyweight for single-foot landing and 35.1 percent for both feet landing when compared with normal gait. They suggested from their findings that the increased loadings on the lower limbs could be detrimental to patients with unsound weight-bearing limbs and could contraindicate swing-through gait for such cases. Five male and five female normal adult subjects were used in the study. Sankarankutty et al (1979) compared the use of the axillary, elbow and Canadian crutches in relation to the metabolic energy consumption. They found that all the ten normal adult subjects (five male and five female) felt that the axillary crutches were easiest and least tiring to use although higher heart rates were recorded. They pointed out that artificial

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stimulation of the heart is possible when using this type of crutch, since the axillary bar is regularly pressing against the thoracic cage. Wells (1979) found that the kinematics and mechanical energy variations of the two-leg swing-through gait were dependent on both the speed of progression and degree of induced disablement. However, the mechanical energy cost of crutch gait was found to be similar to that in normal gait. Three normal adult male subjects were used in their study. A study by McGill and Dainty (1984) on the kinematics, kinetics and mechanical energy of children's crutch gait, shows the importance of optimal length fitting. Increased energy expenditure and reduced crutch weight-bearing were observed with ill-fitted axillary crutches. Five male and three female normal subjects, ages ranging between 9 and 11 years, took part in their study.

In all the articles reviewed, the use of normal subjects was a common feature. Wells (1979) pointed out that the use of normal subjects in two-leg swing-through gait has repercussions on the results. This is because normal subjects are able to make full use of their legs. Therefore to be more representative of the disabled crutch user, the joints of the normal lower limbs must be immobilized. This may be true in simulating two-leg swing-through gait, especially that of paraplegic subjects. However, in one-leg swing-through gait, the weight-bearing leg of the disabled crutch user is usually capable of normal range of motion and has normal muscle power. Hence, by suspending one of the legs in the normal subject for one-leg swing-through gait, a close approximation of many disabled crutch users can be achieved (Stallard et al, 1978). Furthermore, the advantages of using normal subjects are (1) greater control of parameters,

(2) availability and (3) adaptability of test subjects.

The objectives of this study were to firstly describe the single-leg swing-through crutch gait pattern and secondly, to determine the axial forces acting along the axillary crutches.

Materials and methodology

Ten normal male subjects were used in this study. Table 1 shows the physical characteristics of these subjects. Each subject was required to flex the left knee to simulate impairment so that only the right leg was weight-bearing. The right leg was the dominant side of all the subjects. Adequate training in the use of axillary crutches was given by a physiotherapist. The crutch gait pattern used for all tests was the one-leg swing-through gait with two axillary crutches and landing on the right foot.

Prior to the commencement of the gait trial, each subject was given as much practice as he required to ensure that he landed on the force platform with his right foot or crutch. Each gait trial consisted of the subjects:

- (i) walking normally at their comfortable speed;



Fig. 1. Correct use of crutch, with a three-finger gap between the axillary fold and bar.

Table 1. Physical characteristics of subjects

Subject	Age (yrs)	Height (m)	Body Mass (kg)
ACP	24	1.73	60.6
AEJ	23	1.72	80.5
DHH	24	1.67	53.3
LCA	24	1.74	59.7
LKC	24	1.78	62.0
TBH	24	1.73	61.9
TSC	25	1.72	52.2
TYK	23	1.78	73.5
YCM	24	1.67	47.5
YWK	24	1.76	63.5
Average (σ_{N-1})	23.9 (0.6)	1.73 (0.04)	61.5 (9.8)

(ii) ambulating with axillary crutches using one-leg swing-through gait at their preferred speed with respect to the following:—

- (a) Proper usage of crutches, that is with the axillary bar three fingers (approximately 50mm) below the anterior axillary fold (Fig. 1)
- (b) Incorrect usage, that is height adjusted so that the anterior axillary fold contacts the axillary bar.

For crutch walking, the ground reaction forces of the right foot and the right crutch were taken on separate runs. For normal walking, only data on the right foot was measured. A run was considered acceptable when the foot or the crutch touched the force plate within its proper limits and that the markers on the body and crutch were visible to the cameras. The resulting representative run was taken as the average over three acceptable runs.

Instrumentation

Kinematic data of the one-leg swing-through crutch gait was recorded by a television/computer gait analysis system, trade-named "VICON" (Oxford Metrics Limited, Oxford, England, U.K.). The three-camera system was used in the ipsilateral study. The ground reaction forces of the foot and the axillary crutch during locomotion were monitored by a Kistler force platform (Type 9281B11).

Uniaxial forces were also measured at three different locations on the axillary crutch on the side of the landing (i.e. right) leg. Stallard et al (1980) had shown that the vertical ground reaction to the crutch on the side of the landing

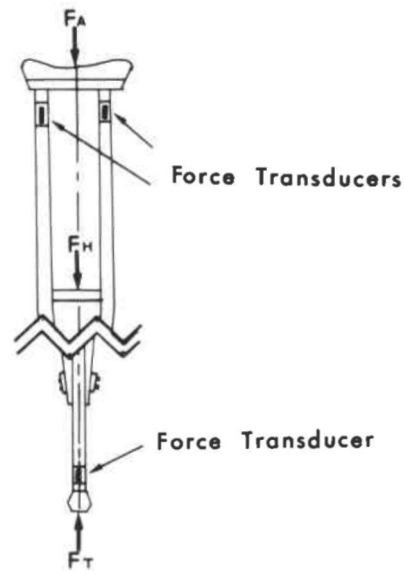


Fig. 2. Lateral view of crutch showing the locations of the force transducers.

leg was on average greater than the contralateral side. Figure 2 shows the three locations where the strain gauges were installed, that is near the crutch tip and the two upper struts of the crutch, close to the axillary bar. The instrumented crutch was calibrated and the three sets of strain gauges were found to respond linearly. The overall error of the force measurements was less than 3 percent. The strain gauges were connected to a 6-channel TML Type DT6A dynamic strain meter (Tokyo Sokki Kenkyojo Co. Ltd., Shinagawa-ku, Tokyo, Japan 140) and the results were plotted on a 6-channel chart recorder.

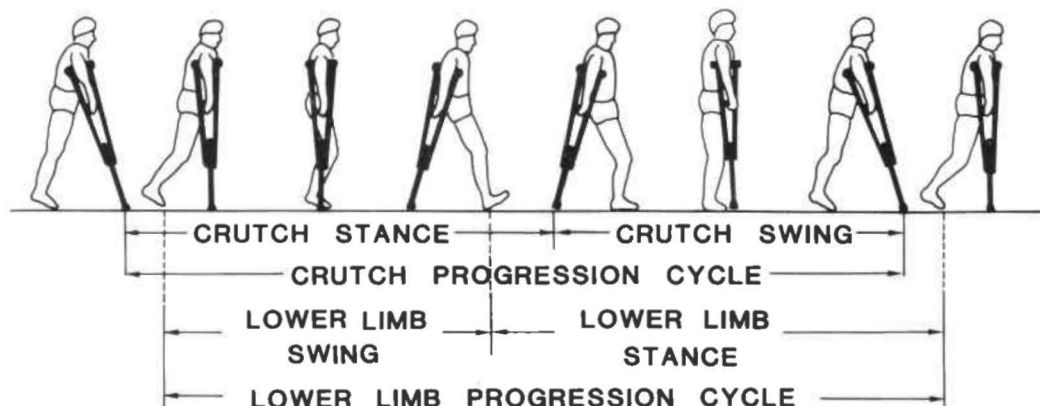


Fig. 3. Gait phases in swing-through crutch gait.

Table 2. Temporal gait data of normal walking and swing-through crutch gait.

	Normal level walking		One-leg swing-through crutch gait			
	Range	Average	Lower limb progression cycle		Crutch progression cycle	
	Range	Average	Range	Average	Range	Average
Stance phase % cycle	59-62	61 (0.9)	69-76	72 (3.0)	52-57	55 (1.6)
Swing phase % cycle	38-41	39 (0.9)	24-31	28 (2.8)	43-48	45 (1.5)
Average speed of progression m/s	1.22 (0.09)		0.73 (0.12)			

Brackets indicate 1 standard deviation (σ_{N-1})

Results and discussion

Figure 3 illustrates the different gait phases during swing-through crutch gait. Table 2 shows the measured temporal details of the gait phases in normal level walking and the swing-through crutch locomotion.

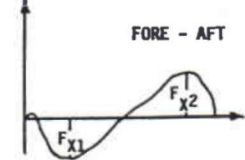
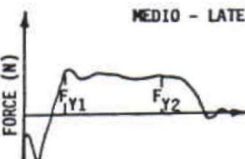
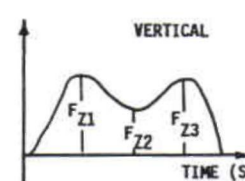
In normal walking, the average stance phase of 61 percent and swing phase 39 percent are in agreement with those reported by other investigators (Murray et al, 1964). The average cycle duration was 1.12s. The cadence ranges from 106-112 steps/min. and the average speed of walking was 1.22m/s. This represents a much slower walking speed than that reported by Murray et al (1964) for the similar age and height groups. The significance of these differences is being pursued in another study.

In the one-leg swing-through crutch

locomotion, the average lower limb stance phase was 72 percent and swing phase was 28 percent. The average cycle duration was 1.66s. Wells (1979) observed that as the degree of disablement increases, the proportion of time spent in double support increases and lower limb swing phase decreases. In this study, the lower limb swing phase decreased by 11 percent as compared to the normal gait. Furthermore, it was found that in swing-through gait the supporting lower limb spent on average 0.82s in single leg stance, this is twice as long as in normal walking. The average crutch stance was found to be 55 percent and swing phase was 45 percent of the crutch progression cycle. The average cycle duration was 1.82s. The average speed of progression was 0.73m/s.

Table 3 gives a comparison of the average

Table 3. Ground - foot reaction forces of the right leg during normal walking and the right "unaffected" leg during swing - through crutch gait.

		Normal walking	Swing through gait	Significance level P
		Average (σ_{N-1})	Average (σ_{N-1})	
 <p>FORE - AFT</p>	Fore - aft shear (% B.W.)			
	F_{X1}	16.8 (4.5)	24.2 (7.0)	<0.02
 <p>MEDIO - LATERAL</p>	F_{X2}	19.4 (3.4)	17.5 (4.8)	N.S.
	Medio - lateral shear			
F_{Y1}	6.6 (1.3)	5.3 (2.7)	N.S.	
F_{Y2}	5.3 (1.6)	0.8 (1.2)	<0.01	
 <p>VERTICAL</p>	Vertical force (% B.W.)			
	F_{Z1}	106.8 (8.4)	128.4 (11.7)	<0.01
	F_{Z2}	74.3 (10.3)	84.2 (8.2)	<0.05
F_{Z3}	106.7 (9.8)	101.2 (5.3)	N.S.	

ground reaction forces of the right foot during normal level walking and swing-through gait. The Student's 't' distribution test was used to evaluate the statistical significance of the results. Differences between averages were considered as significant at $P < 0.05$.

At early lower limb stance of swing-through gait, the fore-aft shear (F_{1i}) was 7.4 percent bodyweight higher than that obtained for normal gait and the vertical force (F_{1i}) was 21.6 percent bodyweight higher. Figure 4 illustrates these increases clearly in the force vector plots. It should be noted that the speed of progression during the crutch gait was much slower than that of normal walking.

Andriacchi et al (1977) have shown that in both normal and abnormal gait there exist either linear or quadratic relationships between various gait parameters and the speed of walking. Wells (1979) observed that by increasing the speed of progression from 0.43 to 0.98 m/s during crutch gait, the range of motion of the lower limbs also increased; the shank excursion increased by approximately 25° and the thighs increased by 10° . Furthermore, the stride length also increased, from 0.75 to 1.2m.

As cited earlier, Stallard et al (1978) have also reported similar increases in the vertical force (F_{1i}), although the speed of progression was not stated. Nevertheless, they cautioned against the

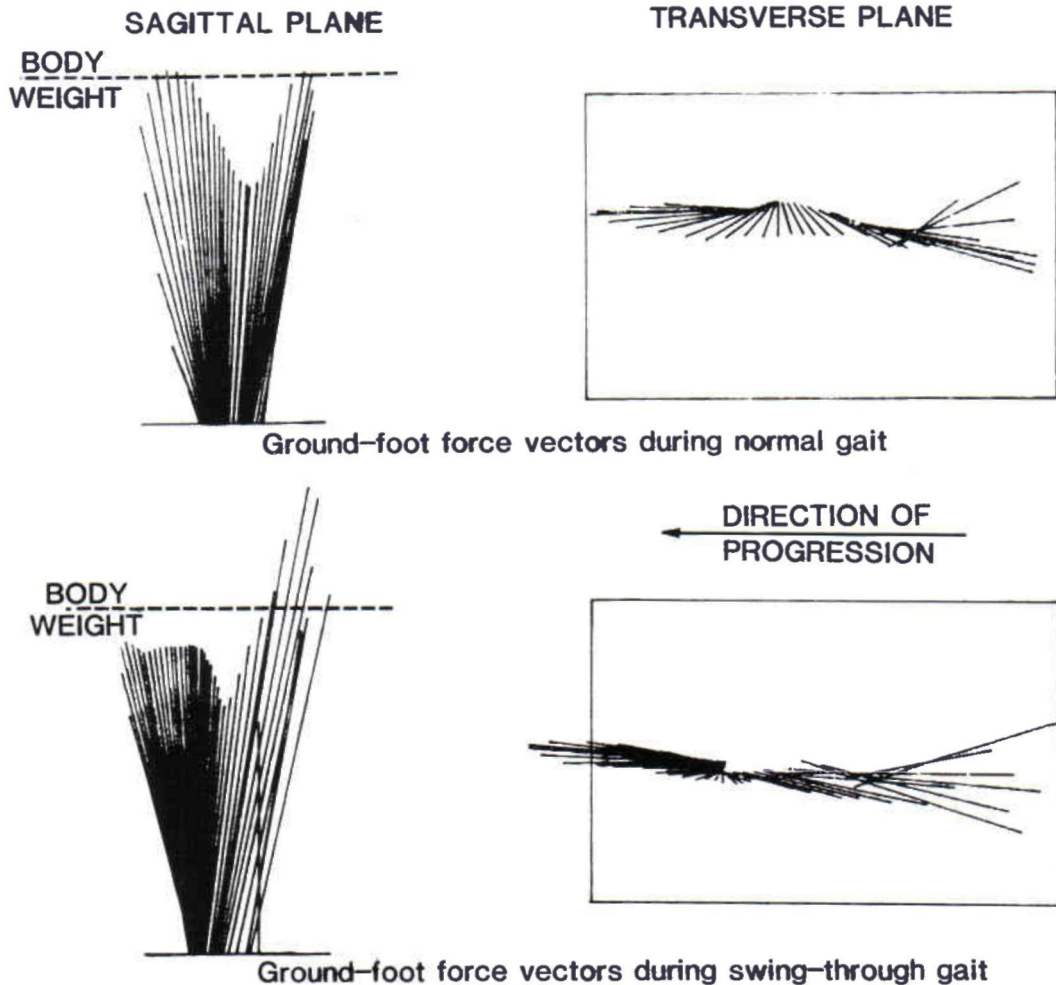


Fig. 4. Typical ground reaction force vector plots of the right leg during normal walking and the right "unaffected" leg during swing-through crutch gait. (Subject LCA).

use of swing-through gait for patients with an unsound weight-bearing limb.

At late lower limb stance of swing-through gait, the fore-aft shear (F_{x3}) and the vertical force (F_{z3}) showed no significant difference when compared to normal gait. However, the medio-lateral shear (F_{y3}) decreased significantly from 5.3 to 0.8 percent bodyweight.

Figure 5 shows the typical pattern of forces developed on the axillary crutches during the swing-through gait when used (a) incorrectly and (b) correctly. When the crutches were used incorrectly, (a) both the upper struts of the crutch were subjected to compression although the forces on the anterior strut showed a much higher magnitude than the posterior. In proper usage, (b) the posterior upper strut of the crutch was subjected to tension while the anterior strut was in compression during crutch stance phase. Table 4 gives the peak forces on the upper half of the body and the crutch tip for both proper and incorrect usage.

In proper usage, the palm experienced a peak force of 44.4 percent of the body weight. This means that both the hands, wrists and forearms virtually bear the whole body weight during the swing-through gait. Therefore, care must be taken in recommending swing-through gait with axillary crutches for patients with weak upper extremities. It could have detrimental effects on the upper extremities and furthermore increase the tendency for these patients to lean on the axillary bar for weight-bearing during gait. This incorrect method of usage will give rise to high reaction forces acting under the armpit. A peak force of 34 percent body weight has been determined. This force could be a contributing factor to crutch paralysis and thrombosis of the axillo-brachial artery through prolonged misuse. Therefore, patients have to be trained not to lean on the axillary bar for weight-bearing.

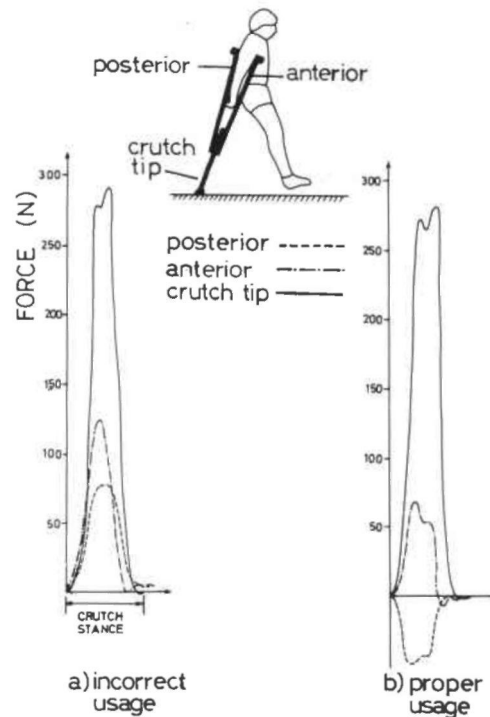


Fig. 5. Uniaxial forces measured along the axillary crutch length during swing-through gait in (a) incorrect and (b) proper usage of crutches (Subject LCA).

An electronic biofeedback device has been designed and developed for use in training for crutch walking. It simply detects and warns the patient of weight-bearing on the axillary bar. The device utilizes the strain gauges mounted on the upper struts of the axillary crutch to monitor the load transmitted through the axillary bar. An empirical value of 15 percent body weight was set as the threshold, any magnitude measured beyond this value will produce an audible output. This value was found to be reliable in

Table 4. Reaction forces transmitted through the axillary crutch during correct and incorrect usage of crutches.

Forces at: (% body weight)	Correct usage		Incorrect usage	
	Range	Average (σ_{N-1})	Range	Average (σ_{N-1})
Axillary bar FA	2.5 – 9.5	5.0 (2.6)	25.6 – 40.7	34.0 (5.7)
Handgrip FH	40.0 – 47.6	44.4 (2.6)	10.9 – 26.1	17.4 (5.9)
Crutch Tip FT	49.3 – 54.4	51.2 (1.7)	50.9 – 54.8	53.2 (1.5)

detecting incorrect usage. The audio feedback allows the patient to make the necessary adjustment.

Conclusion

The study has shown that in one-leg swing-through crutch gait,

- (i) The average limb stance and swing phases were 72 percent and 28 percent respectively; the average crutch stance and swing phases were 55 percent and 45 percent respectively.
- (ii) The peak vertical component of the ground reaction force on the weight-bearing leg during lower-limb stance was 21.6 percent bodyweight greater than in normal walking. This could prove detrimental to patients with unsound lower limbs.
- (iii) The peak reaction force transmitted to the arm during crutch stance was 44.4 percent bodyweight which could be harmful to patients with weak upper extremities.
- (iv) If crutches were incorrectly used, a high compressive force of 34 percent bodyweight was found to be acting on the underarm. An electronic device has been designed and developed to help in monitoring the proper use of axillary crutches.

Acknowledgements

The authors wish to thank Mr. E.J. Ang, Mr. C. P. Ang, Mr. S. Rajaratnam, Miss Belinda Teng and Miss P. L. Tan for technical assistance. Thanks are also due to Miss T. M. Mak and Mr. S. H. Tow for the illustrations and Miss Zaidah for the secretarial assistance.

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