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*Original paper*

# *The influence of a two-point contralateral crutch gait on the loading of the lower limb using a forearm crutch*

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**Abstract**

Objectives: This biomechanical study was conducted to validate the assumption that using an elbow crutch on one side diminishes the loading of the contralateral lower limb.
Methods: This study included in total 49 subjects: 39 patients and 10 healthy volunteers with a total of 114 observations divided in two groups. Group I, control group, (forearm crutch) contained 24 subjects (5 healthy volunteers and 19 Orthopedic patients). Group II (electronic forearm crutch) was made up of 25 subjects (5 healthy volunteers and 20 Orthopedic patients) with 60 observations. The electronic crutch recorded the speed of the crutch movement in the sagittal plane, the axial force exerted on the shaft of the crutch and the position of the crutch in the frontal plane in relation to the central axis of the subject.
Results: holding the forearm crutch contralateral of the examined limb, we documented a 74% lower amount of limb loading.
Holding the elbow crutch on the same side as the examined limb, we reported in 53.6% less loading.
Conclusions: These results do not corroborate with the theoretical mechanical analysis of limb loading, where a diminishing load of the limb is predicted contralateral to an elbow crutch.

**Keywords** Fracture care, walking aids, biomechanics of walking, force platform

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## Introduction

Walking aids are often used as an essential rehabilitation tool to help patients in their functional recovery during treatment for an orthopaedic ailment. The simplest way of walking aid is the cane. With the walking stick, the transmission of force to the ground is via the forearm and wrist. The weaker forearm muscles limit the transmission of forces via the walking stick to the ground. With the forearm crutch, due to the double contact (wrist and forearm), the transmission of force is much more efficient in magnitude and in time. The use of a crutch broadens the base of support of the patient, improving balance and reducing the load placed on one of the lower limbs (**Kaye 2000, Alexander 1996, Verbrugge 1997, Whittle 2012**). Although crutches are often prescribed by a physiotherapist to facilitate post-operative walking, an exact determination of the forces acting on the affected limb in specific clinical situations are difficult to obtain (**Brand 1980, Rasouli 2019**). There are many types of crutches. For this study we utilised the forearm crutch, also called Lofstrand or Canadian crutch. This crutch has a cuff at the end that goes around the forearm (**Whittle 2012**). This study aimed to validate the assumption that with a two-point contact gait, the contralateral leg opposite from the crutch receives a lesser load while the leg next to the crutch takes a greater load.

## Materials and Methods

We reported on 49 subjects (39 patients and 10 healthy volunteers) to participate in the current study. The patients were allocated according to the first-come, first-served principle. They had all different orthopaedic ailments of their lower leg and were at the end of their rehabilitation period. No patient refused to take part in this study. Walking patterns were defined in both groups by the walk ratio. The walk ratio, step-length divide by step-rate, is a speed independent index of walking (**Sekiya 1998**).

There was a significant difference in walking ratio between the young healthy subjects (0.033) and the patient group (0.019). Group I, control, used a forearm crutch and included 24 subjects: 5 healthy volunteers (5 females) with a mean age of 43.6 (range: 23–80) years and 19 orthopaedic patients (12 females and 7 males) with a mean age of 33.0 (range: 21–45) years. The difference in age and weight between the volunteers and patients was significant (p = 0.0087 and p = 0.0160, respectively). Group II included subjects who used an instrumented, electronic elbow crutch (Figure 1) and contained 25 subjects: 5 healthy volunteers (2 females and 3 males) with a mean age of 28 (range: 25–32) years and 20 patients (11 females and 9 males) with various orthopaedic ailments with a mean age of 52.5 (range: 22–69) years. The difference in age between the volunteers and patients was significant (p = 0.0004).

In addition, only age was significantly different between Groups I and II.

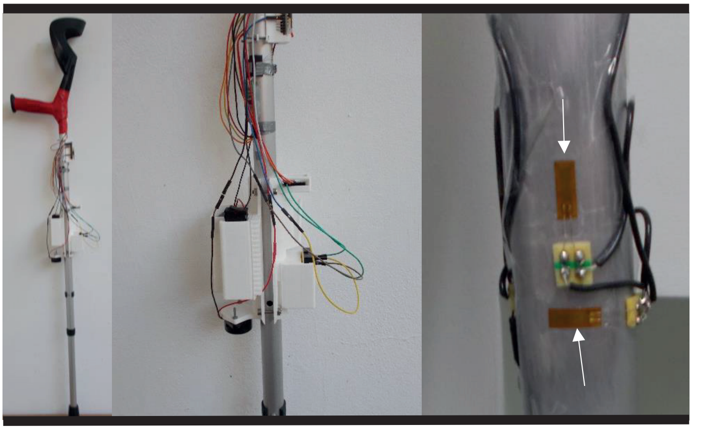

**Figure 1.** Instrumented crutch with the full Wheatstone bridge configuration (white arrows)

We made in total 114 observations: 54 in Group I and 60 in Group II. An observation was defined as an episode of walking with a crutch. In both groups, we combined the crutch with a foot pressure plate (Footscan 9, RSScan, Belgium) to determine the amount of load being exerted beneath the foot. The instrumented crutch used in this study is a unique instrument which records the axial force on the crutch, the crutch's angular speed in the sagittal plane and the crutch's position in the frontal plane relative to the axis of the body. It is described in detail in a previous publication (**Reynders-Frederix 2020**) .The foot pressure platform assessed the load distribution in time and also per area on the sole of the foot. The pressure with this system is expressed in Newton/cm $^{2.}$ We chose to use a two-point contralateral crutch gait, the crutch on one side is moved forward on the same time as the contralateral limb, because this type of support is often prescribed at the end of the revalidation period following an orthopaedic injury (**Smidt 1980, Stallard 1980, Pierson 1994**).

Before testing each participant, we calibrated the axial force exerted on the crutch using a compression bench (Tinius Olsen H5KL-Salfords UK). For this step, the bottom region of the crutch was dismantled and positioned on the compression bench. The crutch underwent cycled compression at 100 N, and the value noted on the compression bench was compared with the recorded force/time curb on the PyCharm display.

Before the observation, the participants were asked to practice walking with regular elbow crutches for 15 minutes. After that, they were asked to walk with bare feet across an inside trajectory course three times for a distance of 10 metres (30 metres) without and with an elbow crutch. Walking test was done on a nonslip conductive rubber walkway. The test was repeated for every crutch position (contralateral/ipsilateral from the injured leg).

In Group II (instrumented crutch), the axial force on the crutch shaft, the angular velocity of the crutch in the sagittal plane and the crutch positions in the frontal plane were recorded by a portable computer equipped with Bluetooth capabilities. The position of the crutch in respect to the body axis, is represented by a curve with both positive and negative areas. An index was created determined by dividing the positive area by the negative area.

An index > 1 indicated that the crutch was leaning away from the body's centre and that the patient was putting more pressure on the crutch, while an index of < 1 showed that the crutch was kept closer to the midline of the body with more pressure on the contralateral limb.

A force plate that was 50 x 50 cm in size was placed in the middle of the trajectory. This foot scan obtains precise plantar pressure measurements using 4096 sensors at a scanning rate of up to 300 Hz using Footscan 9 software (Rsscan, Beringen, Belgium). The loading of the ipsilateral and contralateral crutch, as recorded by the force plate, was measured in five timeframes at 10%, 25%, 40%, 60% and 80% of the stance phase and compared with the recordings without an elbow crutch (Figure 2).

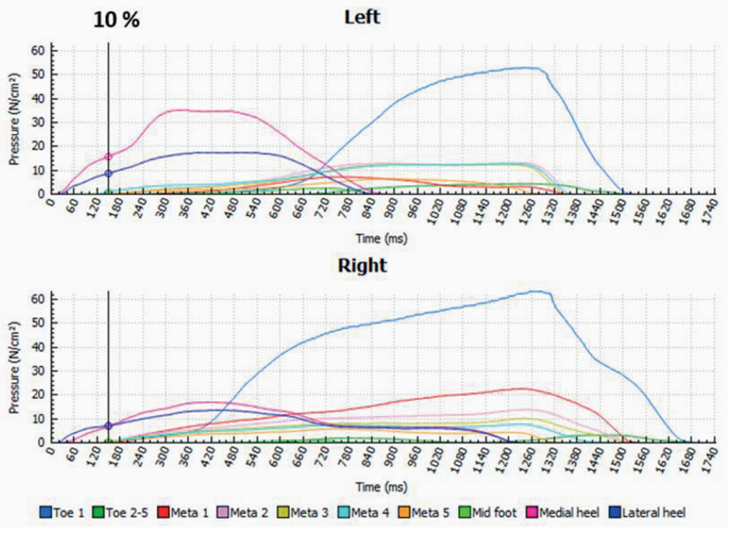


**Figure 2.** Normalizing pressure for time. Five time frames at 10 %, 25%, 40%, 60% and 80 % from the stance phase were used to calculate the pressure.

### *Design of the instrumented crutch*

The crutch used in the current study was a standard elbow crutch with an aluminium frame that was selected because of its lightness (2.700 kg/m$^3$), tensile strength (70–700 MPa) and Young's modulus (69 GPa). The prototype was built by the BEAMS department at Free University in Brussels (**Reynders-Frederix 2020**) (Figure 1).

We installed four strain gauges as a full Wheatstone bridge to assess the pure amount of compression on the crutch shaft. In addition, a gyroscope and tri-axial accelerometer (GY-521) were used to determine the roll and pitch angle of the crutch. Finally, a microcontroller (Arduino Uno) sent the data via Bluetooth to a developed end-user programme created in Python (ESP32). Synchronous readings of the different biomechanical parameters were carried out using PyCharm (PyCharm version 2019.1.3; JetBrains Czech Republic).

## Statistics

GraphPad Instat® 3 (San Diego, California 92108, USA) software was used for statistical calculations. The statistical analysis assessed the Gaussian distribution using the Kolmogorov-Smirnoff test. An unpaired nonparametric Mann-Whitney U test was chosen to compare the means. The regressions and correlations were tested with multiple X variables (multiple regression). The level of significance was set at 5%. To calculate the ideal sample size and its power, we used GraphPad StatMate® (San Diego, California 92108, USA).

## Results and discussion

We included 49 subjects divided into two groups for a total of 114 observations (Group I: 24 participants with 54 observations; Group II: 25 participants with 60 observations). Both groups did not differ significantly in their weight, height or shoe sizes. There was a significant difference in age between Groups I and II (mean age in Group I: 43.35 [range: 23–80] years and mean age Group II: 52.7 [range: 22–75] years; p=0.0043).

In 114 observations, we observed less force on the limb contralateral to the crutch in 74% (43 of 58 observations) of subjects with a mean of -14.6% (range: -1% to -46%) and an SD of 12 (95% confidence interval [CI]: -10.3% ± -18.5%). In 26% (15 of 58 observations) of subjects, there was an increase in force loading on the limb contralateral to the crutch with a mean of +7.3% (range: +1% to +10%) and an SD of 5.9% (95% CI: +9.8% ± +4.7%).

In 53.6% (30 of 56 observations) of subjects, there was less loading on the limb ipsilateral from the crutch with a mean of -15.75% (range: -1% to -34%) and an SD of 10.3 (95% CI: -11, 37% ± -20, 13%). In 46.4% (26 of 56 observations), more loading was recorded on the limb ipsilateral from the crutch with a mean +13.8% (range: +1% to +35%) and an SD of 10.36 (95% CI: +17.6% ± +9.9%).

There was a significant difference in the number of cases with positive loading of the limb opposite the crutch (CL) with the positive loading of the limb nearest the crutch (IP) in Groups I and II. A descriptive analysis of the test results and their significance in Groups I and II is shown in Tables III and IV. In Group I (normal elbow crutch), we found a significant difference in the number of positive (more loading) and negative (less loading) loading of the contralateral limb (opposite from the elbow crutch) and ipsilateral limb loading (same site as the crutch). The descriptive statistics of Group I (normal elbow crutch) and also the subject- and crutch-specific variables are shown in Table I.

**Table I**. Descriptive statistics of Group I (normal elbow crutch): subject- and crutch-specific variables.

| **Characteristics** | **Variables** | **Variables** | **p-value** |
|---|---|---|---|
| CL | Group I | Group II | 0.1805 |
| IP | Group I | Group II | 0.5640 |
| Age (Group I) | Age | IP | 0.3708Ω NS |
| Age (Group I) | Age | CL | 0.9668Ω NS |
| Weight (Group I) | Weight | IP | 0.2116Ω NS |
| Weight (Group I) | Weight | CL | 0.5913Ω NS |
| Height (Group I) | Height | IP | 0.8881Ω NS |
| Height (Group I) | Height | CL | 0.6764Ω NS |
| ***IP (Group I)*** | ***More load*** | ***Less load*** | ***<0.0001**** |
| ***CL (Group I)*** | ***More load*** | ***Less load*** | ***<0.0001**** |
| IP (Group I) | Patients | Volunteers | 0.1426§ NS |
| CL (Group I) | Patients | Volunteers | 0.2235§ NS |
| CL (Group I) | Male | Female | >0.9999§ NS |
| IP (Group I) | Male | Female | 0.3698§ NS |
| ***More loading*** | ***CL Groups I and II*** | ***IP Groups I and II*** | ***0.0157**** |
| Less loading | CL Groups I and II | IP Groups I and II | 0.445§ NS |
| Ratio neg. vs pos. | CL Groups I and II | IP Groups I and II | 0.132§ NS |

*****Mann-Whitney U test/**§**Fischer's exact test/**Ω** Correlation: Spearman rank/**NS**: not significant
**$**: unpaired t-test/**IP**: Loading on the lower limb near the crutch/**CL**: loading on the lower leg contralateral from the crutch.

In Group II (electronic crutch), when examining loading forces exerted on the contralateral and ipsilateral limb, we found that the difference between more loading versus less loading was significant. In these same subjects, we found a correlation between the loading of the ipsilateral limb (near to the crutch) and tallness. Tall participants had a greater load on the ipsilateral holding crutch that was significantly greater than that of participants with a shorter height.

In a multiple regression analysis within the patients and volunteer groups, we could not find any correlation between limb loading contralateral or ipsilateral from the used crutch and the force exerted on the crutch, the angle velocity of the crutch in the sagittal plane or the position of the crutch in relation to the centre of the body. In addition, the position of the crutch in relation to the centre of the body did not differ between volunteers and patients.

The descriptive statistics of Group II (instrumented crutch) subject- and crutch-specific variables are shown in Table II.

**Table II**. Descriptive statistics of **Group II** (instrumented elbow crutch): subject- and crutch-specific variables.

| **Characteristics** | **Variables** | **Variables** | **p-value** |
|---|---|---|---|
| *CL* | *Positive (more)* | *Negative (Less)* | *0.000** |
| Length/Position | Length (subjects) | Position (crutch) | 0.289§ NS |
| *IP* | *Positive (more)* | *Negative (Less)* | *<0.0001** |
| CL | Patients | Volunteers | 0.6206§ NS |
| IP | Patients | Volunteers | 0.4118§ NS |
| IP | Male | Female | 0.1032§ NS |
| CL | Male | Female | 0.6980§ NS |
| CL | Tall (>1.63 m) | Short (<1.63 m) | 0.6683§ NS |
| *IP* | *Tall (>1.63 m)* | *Short (<1.63 m)* | *0.0498§* |
| CL | CL | Force on crutch | 0.7434Ω NS |
| IP*** | CL | Force on crutch | 0.2921Ω NS |
| CL | CL | Weight | 0.0520Ω NS |
| IP | CL | Weight | 0.3636Ω NS |
| CL | Old (>60 years) | Young (<60 years) | 0.3003§ NS |
| IP | Old (>60 years) | Young (<60 years) | 1.0§ NS |
| IP | CL | Age | 0.5374Ω NS |
| CL | CL | Age | 0.8195Ω NS |
| Force/Position | Axial force on the crutch | Position of the crutch | 0.2326Ω NS |

*Mann-Whitney U test/**§**Fischer's exact test/**Ω** Correlation: Spearman rank/**NS**: not significant/*** when holding the crutch on the same side of the limb, there is a relationship between the force exerted on the crutch and the amount of contralateral limb loading.**CL**: Load on the lower leg contralateral to the crutch.**IP**: Load on the lower limb near the crutch.

***Multiple Regression Analysis***

*Multiple regression **Load Contra Lateral Leg** as the dependent variable, or **Y**, and **Force, Velocity** and **Crutch position** as independent variables or X.

Equation that fits the data the best.

Load CL = 108.82 + 0.05322 (Force) – 0.4249 (Speed) – 0.06542 (Crutch position)

R squared = 21.95%

The P-value is 0.0972, which is not considered significant.

*Angular speed makes a significant contribution.*

*Multiple regression **Load Ipsilateral Leg** as the dependent variable, or **Y**, and **Force, Velocity** and **Crutch position** as independent variables, or X.

Equation that fits the data the best.

Load Cr = 100.15 + 0.04791 (Force) – 0.1668 (Speed) – 0.4370 (Crutch position)

R squared = 8.54%

The P-value is 0.5528, which is not considered significant.

*No variable made a significant contribution.*

The decision to use a crutch is based on a theoretical model that calculates the condition of equilibrium of the pelvis during a slow gait in a stance phase, where one foot is on the ground and the other is lifted off the floor (**Whittle 2012, Brinckmann 2016**). Because the progression in walking is slow, it is assumed that the inertial (horizontal) forces generated during acceleration and deceleration during the stance phase are negligible.

In this situation, there is an equilibrium between the *gravitational weight of the body minus one leg* which is in a swing phase and the *contraction force of abductor muscles of the loading hip.* Adding a crutch on the opposite side as the injured leg diminishes the abductor muscle force needed for this equilibrium. The theoretical reduction of the load on the lower leg opposite the crutch equals five times the force between the hand and the crutch (**Brinckmann 2016**) (Figure 3).

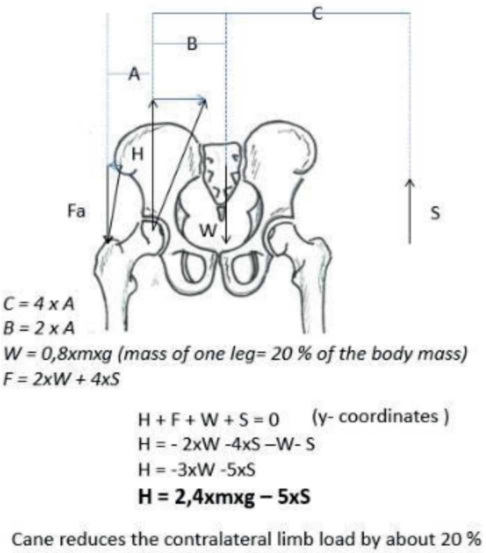


**Figure 3.** Theoretical analysis of the mechanical influence of unloading the leg using a crutch on the contralateral side.

Knowledge of this principle is paramount and is often used in the post-trauma revalidation of patients. In our study, we combined the data obtained from the electronic crutch and force platform in a group of healthy volunteers and in a group of Orthopedic patients. We could not corroborate this presumed correlation between the position of the crutch in relation to the centre of the body and the loading of the limb.

In our study, out of a total of 114 observations (an observation was defined as a bout of walking with a crutch), 15 out of 58 observations gave rise to more loading of the limb opposite to the one holding the crutch. In 43 out of 58 observations, there was less loading force exerted on the contralateral limb. The variation of less loading was important (range: -1% to -46%).

When the limb loading force near the crutch was examined, 46.6% of our subjects demonstrated a greater loading force, with a mean of +13.8% (range: +1% to +35%).

This study also produced a few other observations. Although the patient group differ from the healthy volunteer group in walking patterns (walking ratio). There was no difference in the loading characteristics between the volunteers and the patients. In addition, we were unable to find a correlation between the force exerted on the crutch and any reduction of the limb loading opposite the crutch. Other factors (such as age, weight, height, crutch position or sex) did not influence the loading or unloading of the crutch on either side of the body.

The most striking result was the unreliable and unpredictable change of limb loading with crutches. The fact that the reduction in loading can vary this much is difficult to understand. In some cases, patients may unintentionally exert more pressure on the affected lower limb, which is potentially dangerous and may jeopardize the healing of the skeletal injury (**Aro 1993**).

There is no clear explanation for our results. The literature on this topic is scarce. Statistical analyses of our data revealed only a significant contribution of height and weight to the loading forces of the leg near the crutch. We hoped to partially explain the results with the positioning of the crutch during walking. It seems reasonable to consider overloading of the leg contralateral from the crutch when the patient's body is leaning towards the affected leg. However, we did not find a significant influence of the crutch position on the contralateral or ipsilateral leg loading. One possible explanation for our results is the disturbed proprioception of the injured leg. With this disturbance of proprioception, the damping of the surrounding muscles' is reduced or absent. An indication for this can be found in the volunteers' results in Group II, where all subjects reduced the load on the leg contralateral from the crutch. This effect was not seen in the volunteers of Group I. Also, the Hawthorne effect plays probably a role in which studied subjects could artificially adapt their walking style (**Levitt 2011**).

The work of Bergmann explained the importance of the subject's muscular tonus. His in vivo measurements of a hip prosthesis revealed that significant variations in hip contact forces exist in the presence of a disturbed gait. Bergmann hypothesized that these exceptionally high peak contact forces are partly due to muscular dysfunction (**Bergmann 2001**).

A limitation of this study is that the patient population in both groups was heterogeneous. We hypothesized that the walking patterns and lack of proprioception would be the same for all patients. Nevertheless, it is still possible that one orthopaedic pathology has more effect on the load transmission of the crutch than another. Another limitation is the length of the pathway. It is possible that with a more extended walkway, walking would be more fluent, less artificial, than with the short walkway (10 m) we used in this study. Also, targeting the pressure platform in the middle of the walkway could hinder the walking pattern of a subject. Another limitation could be that the same study persons did not use both types of crutches. However, we found only a difference in age between the two groups. Even then, the outcome was the same in both groups. Another pitfall when making pressure measurements with pressure platforms is that patients with the painful area will not fully load this area to avoid pain. In this case, lower pressure will be recorded. We did not have patients with an ongoing painful foot sole in the patient group. The strength of the present study is the inclusion of orthopaedic patients and able-body subjects. In most studies, only healthy persons were used for the gait analyses. Another strength was the inclusion of standard crutches beside the instrumented crutch. Because of encasing issues, seen with the instrumented crutch, it was thought that adding a standard elbow crutch would better reflect the normal walking behaviour of the study subjects.

## Conclusions

In the present study, we could not corroborate the commonly cited concept of orthopaedic and rehabilitation medicine that the load of a leg contralateral from a used crutch is less and the leg load near the crutch is more. In post-surgery physiotherapy, one crutch can be valuable to keep a patient's balance but is likely not enough to protect the injured lower limb from overloading. Considering the seemingly considerable and unreliable variation in lower limb loading opposite from the crutch, our data indicate that walking with two crutches throughout the rehabilitation phase seems safer.

### Ethical review statement:

The ethics committee does not raise ethical or legal reservations against a publication of the results of this project. Permission of the clinical research ethical committee was obtained: CE 2020/90 BUN:B0772020000023, 09.06.2020.

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