

IMECE2017-71961

**ASSISTIVE FORCE REDIRECTION OF CRUTCH GAIT
PRODUCED BY THE KINETIC CRUTCH TIP**

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ABSTRACT

This paper investigates how crutch tip designs affect the user's gait. Five Kinetic Crutch Tips (KCT), each with different durometers (i.e., stiffnesses) along with one carbon fiber reinforced nylon 3D printed KCT and one Standard Rubber Tip were tested. The first experiment examined eight healthy subjects to determine the assistive horizontal force generated and crutch angle range. The second experiment eliminates the human factor and uses a weighted crutch in free fall to investigate transitional angles between forward and backward motions. It was found that the KCT had a larger transitional angle than the Standard Rubber Tip. This increases the assistive forward forces of the crutch due to the surface kinetic shape of KCTs; however, the total angle of different crutch tips remains the same when used by the subjects. The assistive forces were present for the longest amount of time for the highest durometer KCT.

INTRODUCTION

Crutches are used as assistive walking devices for a broad demographic. They help aid gait impairments ranging from short-term use such as sprained ankles, to long term use as in the case of cerebral palsy [1]. Crutch users also vary from children, teens, adults, and the elderly. Because of this wide range of applicability, there are variations in the design of a crutch. The two main types of crutches used are underarm and forearm crutches. For these crutches, the interaction of the crutch tip with the ground has been analyzed to produce different types

of crutch tips aimed to address the drawbacks associated with conventional crutches. Non-slip crutch tips aim to improve the safety of crutch usage in wet weather, ice, or snow [2]. Some crutch tips attempt to dampen the impact of the crutch tip with the ground to make crutches more comfortable for the user [3]. One issue that has not been adequately addressed is the inefficiency of crutches. Studies have shown that crutches require at least twice as much energy when compared to normal walking [4]. This can cause fatigue and discomfort to crutch users, which hinder the effectiveness of a crutch. Advancements that have attempted to resolve this issue include a spring-loaded crutch and a rocker bottom crutch. However, both of these variations have not shown significant improvements in energy efficiency [5, 6].

There have been various crutch tip designs patented in order to prevent slip [7], improve stability [8], and reduce impact forces [3]. However, the authors could not find any research results that demonstrate the effects of these advancements on reducing walking energy and improving crutch assistive forces.

A different type of crutch tip, the Kinetic Crutch Tip [9, 10], has been developed to passively assist a crutch user's forward motion using a spiral curved shape. Although few crutch tip designs have suggested radial shapes [11], there are no other designs with a varying radius for crutch tips. This crutch tip could also influence other walking parameters due to its kinetic shape. For these reasons the impact on gait using a different type of crutch tip is worth looking into for energy efficiency as well as user performance.

This paper investigates the improvement of crutch angle range and positive horizontal force percentage of KCTs. It

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also compares transitional angles (i.e., the switch from forward motion to backward) of KCTs and Standard rubber tip and indicates a shift in the average transitional angle values for KCTs.

BACKGROUND

The KCT utilizes a non-constant radius kinetic shape in order to passively assist the user's forward motion during the swing phase of gait. The idea behind this crutch tip is that variable radius objects tend to roll in the direction of decreasing radius [12]. This occurs because the force the user applies through the crutch is offset from the contact point of the ground due to the curvature of the KCT. The moment generated from this offset can help propel the user forward when walking up a hill or on level ground. If the KCT is turned around, it can also resist forward motion when walking downhill and help to keep the person in control during the descent.

A previous study has been conducted that supported the assistive and resistive forces the KCT was able to passively generate due to its orientation [9]. The current study intends to investigate the impact KCTs have on the angles a crutch can swing through, the amount of time assistive forces are present, and the transition angle where a given crutch tip will change from falling backward to falling forward. Additionally, a lower angle for the transition point corresponds to a larger distance the user can reach forward for crutch strike, allowing a greater distance to be swung through. Swinging through a larger angle on a crutch would allow the user to cover more distance per gait cycle. A crutch tip that provides an assistive force for the longest time improves the efficiency of a crutch. These factors are evaluated on different durometer (i.e., stiffness) levels for the KCT as well as a standard tip for comparison.

DESIGN

As mentioned above, a Kinetic Shape [12] helps generate forward motion by redirecting vertical forces to horizontal ones. The KCT uses this advantage to increase assistive forces in the direction of movement. As can be seen from Figure 1-a, there is no moment generated in a standard tip on a flat surface since both ground reaction and vertical applied weight are aligned. However, the misalignment of forces in a KCT (Figure 1-b) has created a moment couple that propels the user forward.

In the case of walking on an inclined surface, the point of contact with the ground moves further. This shift creates a backward momentum in a standard tip that causes a resistive moment in the opposite direction of walking (Figure 1-c). For a KCT on an inclined plane, this opposite force has been eliminated and replaced by an assistive momentum up until both reaction force and vertical weight are aligned (Figure 1-d). Note that this is illustrated for a crutch in the vertical position, but similar benefits are generated at other angles.

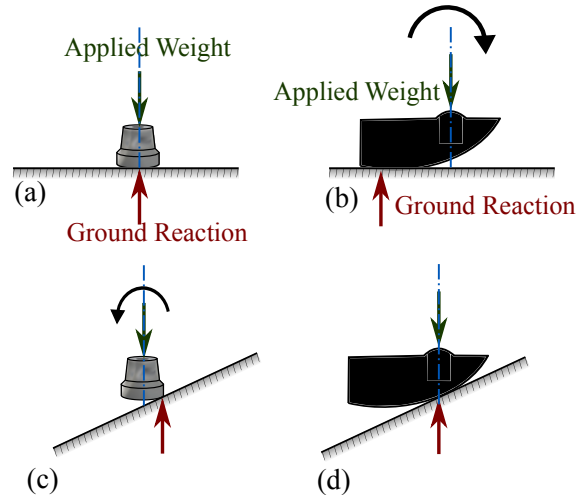


FIGURE 1. REPRESENTATION OF FORCES/MOMENTS ON FLAT AND INCLINED PLANES FOR STANDARD TIP AND KCT

EXPERIMENTS








Two experiments have been conducted. In the first one, eight healthy subjects use different crutch tips during 2-minute walking trials. Assistive horizontal forces and the range of crutch angles during stance phase are studied. The second experiment studies the free motion of crutches without any users so the motion can be studied without any differences between crutch walking styles. The crutch was kept at different angles relative to the vertical axis and released. The direction of motion as well as the initial position were recorded. Different inclined surfaces were tested to compare the stability of different crutch tips.

Experiment 1: Crutch Walking

This experiment involved analyzing the effect a crutch tip had on two factors during dynamic walking: (1) the total angle a crutch swings through and (2) the duration of assistive forces present per gait cycle. The eight subjects that participated in the experiment were between the ages of 20-30 and were healthy individuals that had medium to no experience using crutches. Written informed consent with a protocol approved by the Western International Review Board was obtained from each subject before involvement in the experiment. Each subject was given time to become accustomed to walking with crutches before starting the experiment. They were also given the option to use their preferred leg when walking with crutches; the other leg was kept in the air to simulate a common usage of crutches, such as when a foot is broken and unable to bear weight.

The participants walked on a crutch for two minutes for each of the seven crutch tips shown in Table 1. The crutch tips were given in a random order between participants. The Computer Assisted Rehabilitation ENvironment (CAREN) system was used to conduct this experiment as well as collect data. In order

TABLE 1. CRUTCH TIPS USED IN EXPERIMENTS

Shape	Type	Name	Durometer ASTM D2240 (Type A scale)
Flat		Standard	~
Kinetic Shape		3D	~
		KCT-40	40
		KCT-50	50
		KCT-60	60
		KCT-70	70
		KCT-80	80

to have a comfortable walking pace for each subject, an initial run was conducted to match the walking speed of the subject to the speed of the treadmill. Motion capture markers were placed on the crutch to track its movement and record the angles the crutch swung through for each gait cycle. Data was also collected from force plates on the treadmill to record the amount of time assistive forces were present during a gait cycle.

Experiment 2: Crutch Weighted Fall

The second experiment was conducted to analyze the motion of a crutch free falling without the influence of human variability. Eliminating the human factor enables us to consistently analyze and compare different types of crutch tips. The objective of this experiment is to analyze the free motion of a weighted crutch. The weight serves to simulate the loading experienced on the crutch during walking. Only four of the crutch tips were tested in this experiment: Standard, KCT-60, KCT-70, and 3D. The other three were eliminated since they did not indicate any significant changes based on the human study in experiment 1.

The four crutch tips were tested at three different inclined angles: 0°, 3°, and 6°. These angles were chosen to cover the angles typically allowed by the Americans with Disabilities Act for elevations greater than 6 inches [13]. Specifically, a slope of 1:10 (5.7°) is allowed. For each trial, the weighted crutch was held at various angles and released. The test was repeated 15 times for all 12 configurations (four different crutch tips on three different surfaces). The goal was to find the vertical angle that crutch switches from forward motion to backward. The repeated trials were conducted to account for any variability in releasing of the crutch.

For each trial, the crutch was held at balance in uphill direction. Then, the crutch was released and motion direction (Forward or Backward) was recorded. All data including initial position and time of release was gathered with CAREN system. Each trial was repeated 15 times and each time random (positive and negative) angles with vertical axes for initial position was tested to cover the transitional angle area.

RESULTS AND DISCUSSION

The value of assistive (positive) forces and range of motion for different crutch tips are compared in the first experiment. The second test compares the backward angle and transitional area between forward and backward motion for various crutch tips.

Experiment 1: Crutch Walking

Out of the eight recorded subjects, subject three had to be excluded from the results due to an error with the motion capture data collection. For the rest of the subjects, the angle of the crutch with respect to the vertical axis was known throughout their gait cycles. The average total angle that a subject swung through during a two minute trial on a given crutch tip was found. This angle was averaged between all valid subjects to find the total angle a crutch swung through when a given crutch tip was applied. The results of these angles have been provided in Figure 2.

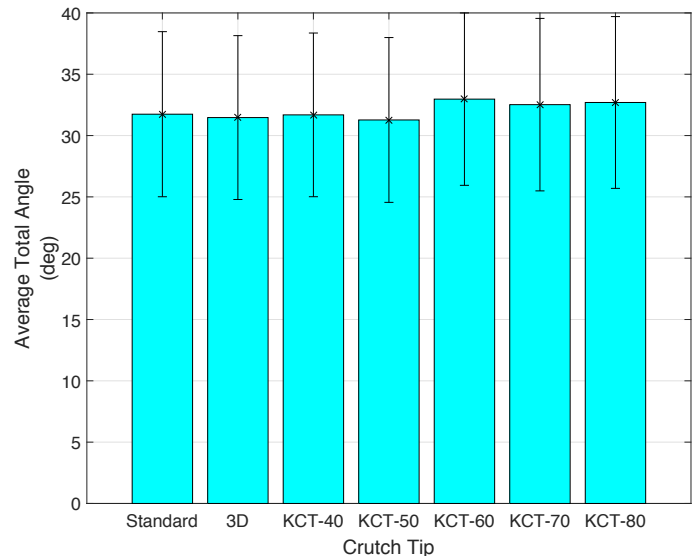


FIGURE 2. AVERAGE TOTAL ANGLE EXPERIENCED BY EACH CRUTCH TIP. THE RESULTS WERE AVERAGED BETWEEN ALL SUBJECTS FOR A GIVEN CRUTCH TIP. ERROR BARS SHOW THE STANDARD DEVIATION.

These results show a nearly identical behavior between each crutch tip. The curvature of the KCT should allow for a greater total angle to be swung through when compared to the flat face of the standard tip. The reason for this discrepancy could be due to the experience level of the subjects. Walking on crutches at a constant pace on a treadmill can be a difficult task for people who do not use crutches regularly. Being concerned about maintaining balance and control during gait could prevent a subject from taking advantage of the ability to swing through a larger angle in order to cover more distance. A future experiment will test the KCTs on chronic users of crutches.

Data collected from the force plates allowed us to know the percentage of time assistive forces were present while a crutch tip was in contact with the ground. This percentage is shown for four crutch tips in Figure 3. The KCT-70 crutch tip had assistive forces helping forward motion for the most amount of time per ground interaction. Assistive forces that are present for a longer time help to increase efficiency since it requires less effort from the user. The crutch tips that offered a longer period of assistive forces were the ones with the highest durometer rating. This is likely because the stiffer crutch tips deflect less when the load of the subject is applied through them. Maintaining the KCT's kinetic shape could contribute to the longer period of assistive forces. Additionally, a less stiff crutch tip could dampen the assistive force generated by the KCT, making it act for a shorter period of time.

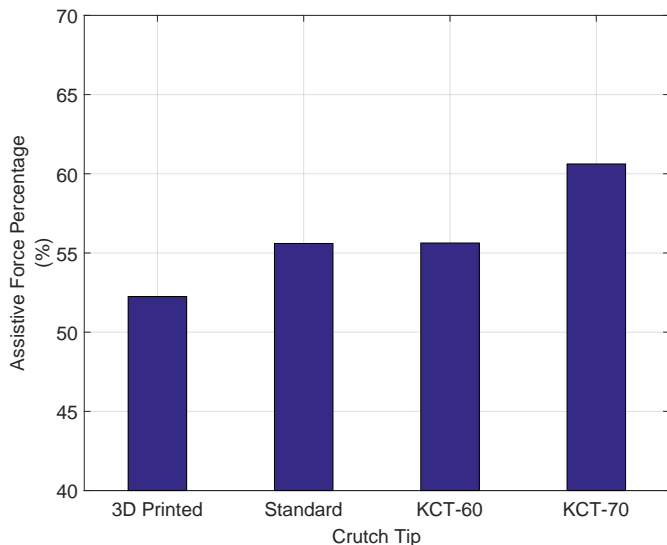


FIGURE 3. PERCENTAGE OF TOTAL TIME DURING CONTACT WITH THE GROUND THAT A CRUTCH TIP GENERATES A FORWARD ASSISTIVE FORCE

Experiment 2: Crutch Weighted Fall

Four different crutch tips were tested on three surfaces with angles of 0°, 3°, and 6°. Figure 4 shows the results for the fifteen drop tests on all twelve combinations of slopes and crutch tips, and the mean value of each transitional angle is shown in Figure 5. Since the crutch was being dropped at different angles (each data point shown), there is a small range of angles (highlighted bar) between forward and backward motion where the direction of movement was not determined since no drops were performed in that area or the crutch fell sideways. In other words, that angle is very near the equilibrium point. The middle of this range is defined as the transitional angle in which the free-fall motion changes from resisting (i.e., backward) to assisting (i.e., forward).

The transitional angle is around 2-3 degrees for KCTs while it is at zero, or negative, degrees for the standard tip. As was expected, the largest forward angles are for the 0° (flat) surface. The standard tip transitions at about vertical, which is as expected since there is no moment generated. All the KCTs were able to generate forward motions even when started at a backward angle. As the surface inclination increased, the maximum backward angle for the forward motion decreased, meaning moving upward gets more difficult. The KCTs still provide some assistance. On all three surfaces, KCTs (3D, KCT-60, KCT-70) indicate larger maximum backward angle than the Standard Tip. As the slope increases, a clear reduction in the transitional angles is visible

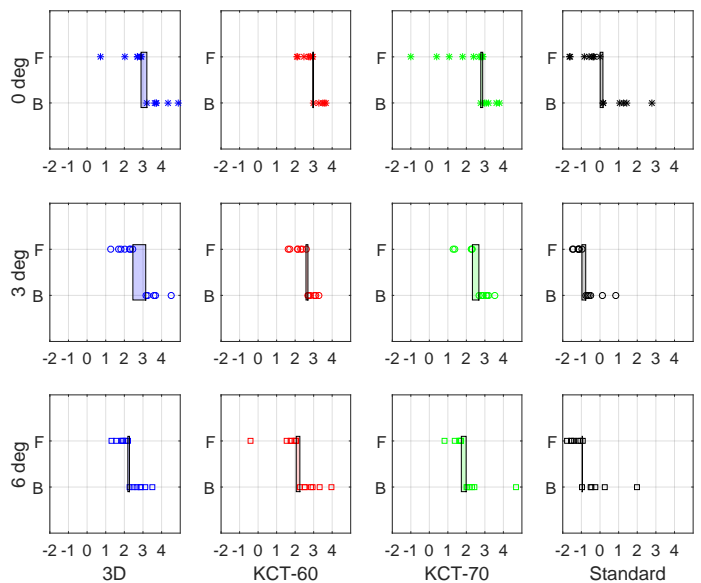


FIGURE 4. TRANSITIONAL ANGLE FOR THE SWITCH BETWEEN FORWARD AND BACKWARD MOTIONS FOR ALL CRUTCH TIPS (F REFERS TO FALLING FORWARD AT THAT ANGLE AND B REFERS TO FALLING BACKWARD).

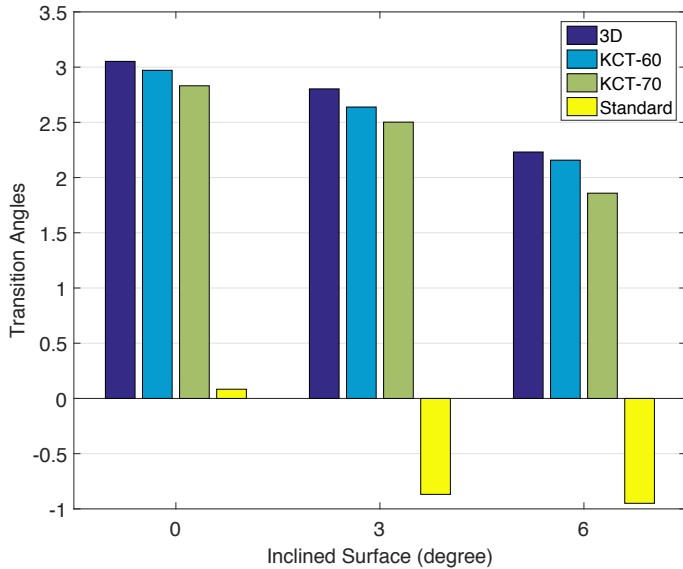


FIGURE 5. AVERAGE TRANSITIONAL ANGLE FOR EACH SURFACE ANGLE WITH EACH OF THE FOUR DIFFERENT CRUTCH TIPS

for standard tip. This means that the standard tip cannot tolerate backward angles with vertical axes as much as KCTs can. The two negative bars indicate that standard crutch tips needed to have a forward angle on 3 and 6 degrees inclined surfaces in order to move forward.

CONCLUSION

Kinetic Crutch Tips with various stiffnesses were introduced in this paper. Two experiments were conducted to evaluate the efficiency of KCTs relative to a standard tip. The first experiment results indicated an increase in assistive forces in the horizontal direction, but the change in the range of motion was not significant. The second experiment purely compared the differences between crutch tips without the involvement of the user. An increase in the maximum backward angle was observed. The results showed that transitional angles for KCTs are larger than Standard tip. This means that KCTs are able to move forward in steeper planes and give the crutch more stability as a result.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant Number IIP-1602020. Kyle Reed has two patents pending related to this work, both with licensing agreements with Moterum Technologies. The University of South Florida also has a financial interest in Moterum Technologies. A management plan has been implemented and followed to reduce any effects of these conflicts of interest.

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