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Quantifying the Benefit of the Kinetic Crutch Tip

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Abstract— **This research focuses on the difference between the Kinetic Crutch Tip (KCT) and a Standard Rubber Tip. Additionally, the effect of KCT stiffness on the crutch gait cycle and the reaction forces were investigated. This study also examined the maximum backward angle that a crutch is able to move forward without any external forces as well as the ratio of positive to negative horizontal forces were considered. The results were obtained in two ways: one by having subjects walk on the crutches and another to reduce the variability of human walking by measuring the resulting motion only using weights attached to the crutch tip. The results of this measurement indicate an increase in maximum backward angle for Kinetic Crutch Tips. This increase in the rotation angle shows an improvement in forward motion of the crutch.**

I. INTRODUCTION

A walking crutch is a type of gait assistive device that transfers weight bearing from the lower limbs to the upper body to relieve stresses on the lower body while also promoting stability. It is often used for people who cannot use their legs to support their weight for reasons ranging from short-term injuries (less than 6 months) to lifelong chronic disabilities.

The walking crutch has been used as a type of mobility aid throughout the ages. A walking crutch is described as a rigid supporting staff with an underarm cross piece that can be traced back to the ancient Egyptians [1], [2], [3]. This historical account generally resembles the currently popular underarm (a.k.a., axillary) crutch. The underarm crutch is used by placing the pad against the ribcage beneath the armpit while holding the grip, which is below and parallel to the armpit pad. Since this first historical reference of the underarm crutch, the design has slowly advanced only in small increments. In the early twentieth century, Emile Schlick patented the first forearm crutch (a.k.a., lofstrand, elbow, Canadian) [4]. This design distributed the user's support forces toward the forearm and away from the wrist of the user.

While underarm and forearm crutches are by far the most widely used types of crutches, these aged designs leave much room for improvement. Many crutch related patents have been filed since 1917 [4] that augment these two core crutch designs. Some of the most notable designs include a crutch with a foot rest support [5], a compliant curved carbon-fiber crutch [6], a crutch with a power lift to raise an individual off their wheel chair [7], an electro-mechanically powered crutch [9], and a hydraulically actuated crutch [8].

There have been several attempts to change the crutch-ground interactions, but none have included the non-constant radius Kinetic Shape [10], [**?**] that is key to the KCT. One attempt to modify and optimize the crutch user's dynamics by changing crutch-ground interactions came in the form of the rocker bottom (rolling) crutch, introduced in 1917 [11], [12]. With this design the user rolls over a large constant radius crutch tip as opposed to pivoting over a point tip. Although the rocker bottom crutch is found to transition smoothly during crutch walking, studies have indicated no direct benefits to the user [13], [14], [15]. That is, using a larger constant radius rocker bottom crutch tip did not alter the user's dynamics or energy efficiency as compared to a smaller constant radius crutch tip (point tip) on the same crutch.

Several crutch tips have recently been developed for the popular crutch designs. The most popular crutch tips available in today's market are shown in Figure 1 (T1-T5). The Adventure™ tip, Figure 1 (T2), is a pivoting tip designed for uneven and slippery terrain. The Tornado™ tip, Figure 1 (T4), is a gel infused crutch tip that dampens crutch ground strike impacts. The SandPad™, Figure 1 (T5), has a large pivoting tip that allows it to be used on sand. Although all these crutch tips vary in weight, compliance, and ground traction, they always mimic a constant radius. A point tip mimics a constant radius when rolled over and cannot change the user dynamics during swinging or rolling over the crutch tip, and all forward progression forces are generated by the user pushing themselves forward over the crutch.

In contrast, the kinetic crutch tip (Figure 2) is able to passively generate customizable assistive or resistive crutch forces and motions during ambulation. Augmenting crutch-ground interactions through crutch tips is practical and cost-effective.

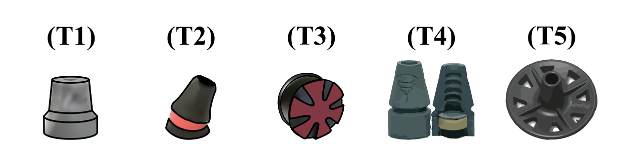

Fig. 1. (T1) Standard Solid Rubber Tip, (T2) Adventure Pivoting Tip, (T3) NonSlip Tip, (T4) Tornado Gel Tip, (T5) SandPad Tip.

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Reed and Handzic have two patents pending related to this work, both with licensing agreements to Moterum, LLC. A management plan has been implemented and followed to reduce any effects of these conflicts of interest.

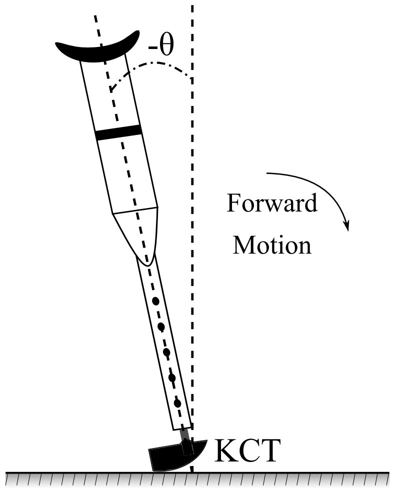

Fig. 2. Crutch Forward Motion with Backward Angle

In this study, the assistive force and crutch backward angle of the KCT and standard tip have been compared. The effect of stiffness on the KCT has also been studied. It is predicted that the kinetic shape of the KCT will increase the positive horizontal forces as well as stability (larger backward angles). These developments improve crutch walking experience, especially for long-term users such as chronically crutch user.

II. KINETIC CRUTCH TIP (KCT)

A. Design

Conventional crutch tips have a standard point or constant radius tip. This type of crutch tip cannot assist or resist the user during pivoting or rolling over the crutch tip, and all forward progression forces are generated by the user pushing themselves forward over the crutch. This property of non-constant radius shape rolling can be precisely defined with the kinetic shape concept [10]. A kinetic shape can be applied in any mechanical situation where exact position-dependent forces and accelerations are required.

Applying the kinetic shape concept to a crutch tip allows the user's downward force to generate a forward force that propels the user forward, thus assisting them to pivot over the crutch. The generated force can be position dependent and customizable. We are able to form the crutch tip such that it will yield a beneficial and predicable user dynamic (i.e., forces and motions). We will refer to this idea of kinetic shapes for crutch tips as kinetic crutch tips (KCTs). The KCT effect is caused by the tip's radius change to create a controlled imbalance at the ground contact point, which causes the crutch tip to push the user forward or backward depending on how the radius changes. A general explanation of the KCT is seen in Figure 3 with a comparison to a conventional crutch tip on an underarm crutch and standing on level ground. Fundamentally, the user steps up onto the larger portion of the KCT radius and rolls down to a smaller radius in order to generate a forward-forcing moment. Past studies have shown that the effects of increasing the crutch height by the height of the KCT at first contact has no

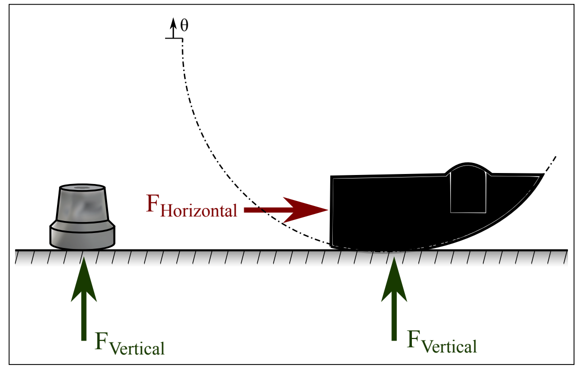

Fig. 3. Ground Reaction Forces to Kinetic Crutch Tip and Standard Tip

significant effect on crutch walking energy cost, cadence, velocity, peak and mean elbow and shoulder moments and impulses [16], [17].

This innovative KCT uses a specially altered shape to predictably redirect the user's downward force (weight) into a propulsive force that assists the individual in forward ambulation. This assistance is provided passively, so no motors or power supplies are required. The assistance force helps the individual use less energy while moving forward over level ground and when walking uphill. The crutch tip shape can be rotated around to reverse the assistance force and provide a more controlled descent down a hill by reducing the user's momentum, although we are not examining that aspect in this paper. The kinetic crutch tip directly addresses two of the common issues mentioned by users, fatigue and stability, which indirectly also helps the comfort of using crutches.

The dynamic effect of KCTs on crutch gait cycle have initially been studied [18]. The experimental results indicated an increase in assistive horizontal forces for a KCT compared to a standard rubber tip. Moreover, additional resistive force was found when using backward KCT. These results proved that KCTs can be altered to adjust to the crutch users' needs. Furthermore, the kinetic shape of the tip could have a beneficial effect on the range of angles that could assist the crutch user when pivoting over crutches from a backward position (Figure 2). Throughout the crutch gait, the angle of the crutch with the normal to ground changes continuously from a negative value to a positive one. The effect of the crutch tip shape on the crutch tendency to pivot forward (crutch backward angle) has been studied in the first experiment. Here, we evaluate how the stiffness of the crutch tip affects motion and further quantify the resulting motion.

B. Stiffness

There are various parameters that can affect the kinetic motion of a crutch tip. Finding a kinetic crutch tip with optimum characteristic that could improve kinetic motion as well as increasing the comfort is important to optimizing the benefit. Here, we are examining the stiffness of the crutch tip.

Stiffness of a crutch has a critical effect on the reaction forces applied to the crutch user. The amount of energy absorbed by the crutch structure could have an indirect effect on the comfort of walking. The material hardness of the crutch tip is one of the key characteristics that could enhance both the dynamic motion and reaction forces during walking. Shore hardness of the crutch tip is important in affecting the structural stiffness of the crutch. Five out of seven crutch tips studied in this research have the same kinetic shape design but with different hardness. The rubber used ranges from a durometer of 40A to 80A. Two other crutch tips include the standard rubber tip as a base for comparison and the 3D printed Kinetic Crutch Tip. The 3D printed model was designed with the same kinetic features as the other five KCTs, but manufactured with carbon fiber reinforced nylon 3D printing. The physical shape and elasticity along with a name associated with each crutch tip in this research has been shown in Table I.

TABLE I
CRUTCH TIPS SPECIFICATIONS

#	Type	Name	Durometer ASTM D2240 (Type A scale)	Shape
1		Standard	~	Flat
2		3D	~	Kinetic Shape
3		MD9	40	Kinetic Shape
4		ME5	50	Kinetic Shape
5		MF3	60	Kinetic Shape
6		MG7	70	Kinetic Shape
7		KCT	80	Kinetic Shape

III. EXPERIMENTS

Two experiments were performed to analyze the crutch tip motion: (1) analyzing the effect of the kinetic shape on the backward pivoting angle for different crutch tips and (2) examining the effects of the Kinetic Crutch Tip stiffness on the crutch gait cycle. The Computer Assisted Rehabilitation ENvironment (CAREN) system was used to capture positions and forces of movements during each experiment. The swing through crutch gait was used for the crutch walking experiment since it is the easiest and most common crutch walking gait for temporary users.

In order to study the pure dynamic movement of a crutch, the human effect should be eliminated. In the first experiment, a setup was designed to release the crutch and record the movement. This experiment helps to compare different crutch tips without the effect of the crutch user's attributes (i.e., height, weight, specific motions, etc.)

The second experiment studied the dynamic effect of the introduced crutch tips on eight participants. The participants walked with swing through non-weight bearing crutches. The ground reaction forces and crutch gait cycle were studied in this experiment.

A. Crutch Free Fall

The purpose of the first experiment was to obtain the maximum backward angle from the vertical axis that the crutch is able to fall forward. In particular, it takes the human variability out of the experiment. The experiment was done for seven types of crutch tips. The shape and elasticity of each one can be seen on Table I. A setup was designed to hold the crutch at a vertical position and release it at various angles. Considering the curvature of the Kinetic Crutch Tips, it is expected that this angle would significantly increase for KCTs compared with the standard tip.

A schematic of this design is shown in Figure 4. As it can be seen, two clamps and a plate were used to hold the crutch at a vertical position on a perfectly balanced surface. The crutch was set to predefined angles and released without any force applied. The negative sign of θ indicates the backward position of the crutch. Small negative angles with vertical axis would cause the standard crutch to rotate backward. However, it is indicated that the kinetic shape of KCTs would redirect downward forces into a forward motion. As a result, this rotation angle is shifted backward, so it almost looks like the crutch is rolling up.

The release structure was designed so that the crutch would not fall to the right or left side. The crutch was held by a pin on the side and marked at different heights. The motion was started by removing the pin and captured using the CAREN system. The experiment was repeated for eight different positions for each crutch tip. The final results indicating the maximum free fall angle of forward motion have been presented in the Results section.

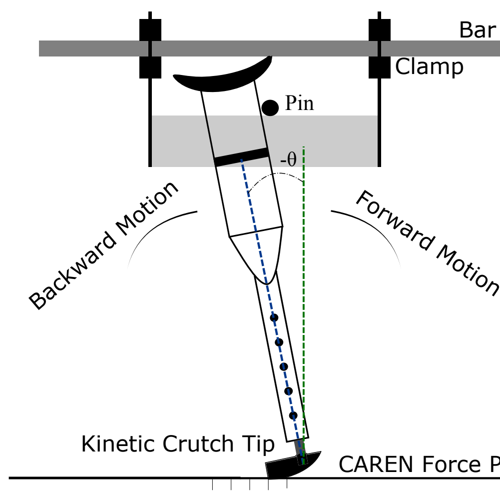

Fig. 4. A schematic of the setup for Crutch Free Fall Experiment

B. Crutch Dynamic Walking

Eight healthy individuals (six male and two female) between the ages of 20 to 30 were asked to walk with crutches using the same seven crutch tips as the first experiment (Table I). Written informed consent was obtained from each subject prior to participation with a protocol approved by the Western Institutional Review Board. They had zero to medium experience walking with crutches.

The crutches were adjusted to the participant's height. All participants had time to get used to the crutches before starting the experiment. The participants were asked to balance on their preferred foot and walk using swing through crutch gait. Only after they were comfortable walking with crutches was the experiment started.

A trial run was conducted on the CAREN to adjust the treadmills' speed to the participant's walking speed. Each trial with a crutch tip was 2 minutes long and all steps during that time period were averaged together. The order of crutch tips were chosen randomly. A total of 56 trials were conducted (8 subjects with 7 trials each). The following measurements were recorded for each trial: crutch gait horizontal forces, step time, step length. Figure 5 shows the setup of this experiment for one of the participants.

Fig. 5. Participant swing through crutch walking on CAREN – Crutch Strike Phase

IV. RESULTS

A. Crutch Free Fall

The first experiment without the subjects' involvement gave measurements of the maximum rotation angle that a crutch could fall forward without any external force (using the setup shown in Figure 4). This angle was calculated using a setup that takes out the human effects on the motion. This experiment enabled us to perceive the net motion of the crutch without a user. The result of this experiment can be used to directly compare various crutch tips. The experiment was done for eight different angles for each crutch tip. The mean value of the maximum angle that each crutch fell forward and the minimum angle that it fell backward was calculated. The results are shown in Figure 6. As expected, the standard crutch tip has the lowest angle (1.23 deg) which means it tended to fall backward more easily. The surface of the standard tip is not perfectly flat which caused the rotation angle to not be zero. However, this angle is still small and indicates that standard tips have the lowest tendency to lean forward and subsequently have the least assistance in aiding the users to move forward. On the other hand, the KCT has the highest angle (3.64 deg) which means it tends to move forward in a larger interval. Stiffness did not seem to make a significant difference for the angle, but this could be partially

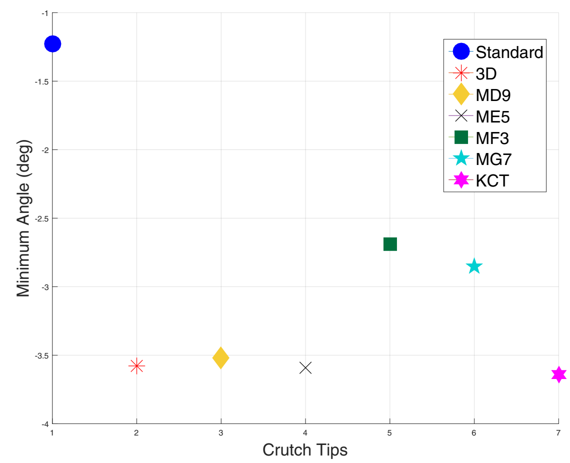

Fig. 6. Maximum Backward Rotation Angle for Different Crutch Tip

due to the smaller amount of weight used compared to the weight of a person.

The assistance effect of this change is noticeable when it is translated into a distance at the top of the crutch, which is where the person is attached to the crutch. This angle is equivalent to approximately four inches at the armpit for a six foot tall person. This distance could be of significant importance for a crutch user with temporary or permanent injuries. The importance of this angle can be seen at the leg swing period of a crutch user's gait cycle. In Figure 7, it is shown that the crutch strikes at a negative (backward) angle and it moves forward as the user swings through crutches.

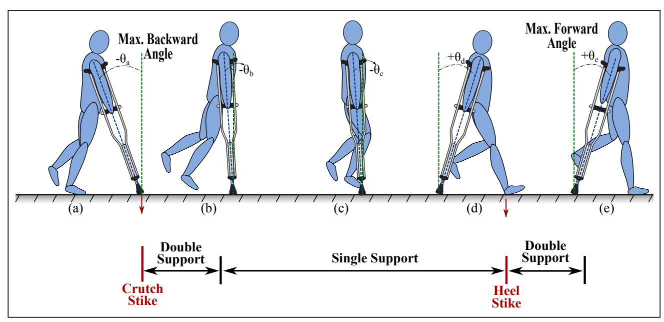

Fig. 7. Swing through crutch gait cycle

B. Crutch Walking

In the second experiment, the goal is to study the difference of crutch gait cycles between the various crutch tips introduced in Table I. In this section, the difference of applied forces in the vertical and horizontal direction and crutch gait step time are studied. The idea is to compare the standard tip with kinetic shape tips as well as comparing kinetic shape tips with various stiffness. In Figure 8, the crutch gait step time for each crutch tip averaged over all eight subjects is shown. The KCT and MF3 had longer crutch step lengths in comparison to the softer crutch tips such as MD9 and ME5. The standard tip and 3D tip had almost the same results. A small visible mismatch between the 3D printed crutch tip and crutch bar could have affected the

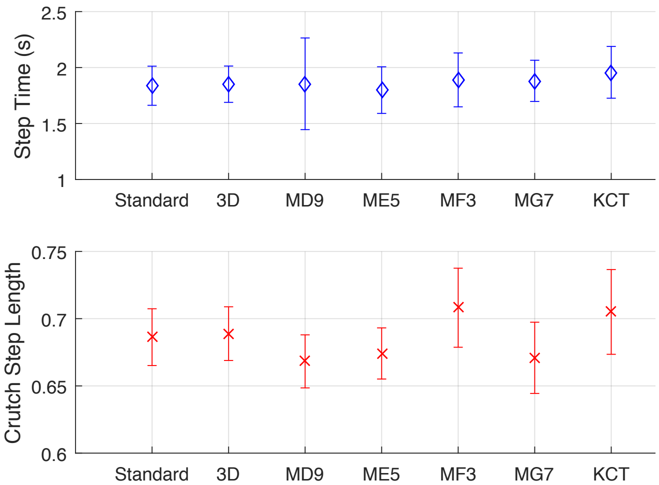

Fig. 8. Crutch Step Time and Length for Different Crutch Tips

result of 3D printed crutch tip. However, the magnitude of differences in step parameters are relatively small.

One of the useful merits that could be applied is the ratio of total positive to negative horizontal forces. The proportion of horizontal forces used in forward motion is indicated by this quantity. This metric indicates the percentage of the time during stance phase that the horizontal force assisted the forward motion. Figure 9 shows this parameter. In addition, Table II indicates the exact numbers.

From Figure 9, it can be seen that MG7 and KCT have the highest values with 60.62% and 61.39%, respectively. Three of the kinetic crutch tips have higher values than standard tip with 55.6%. Crutch tips with the low hardness values (MD9, ME5 and MF3) displayed lower percentages than crutch tips with higher values (MG7 and KCT). This indicates hard crutch tips with higher durometer performed better than softer ones. Furthermore, the 3D printed crutch tip with 52.25% had the lowest percentage. One reason for these results of 3D crutch tip could be a mismatch in the angle

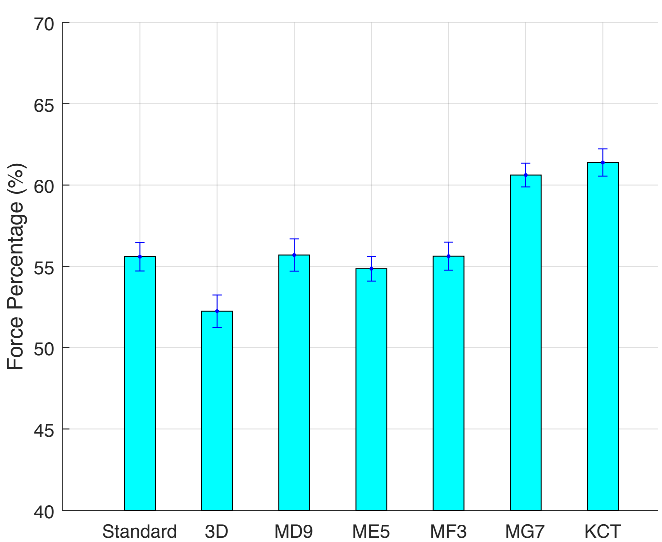

Fig. 9. Percentage of time during stance that the horizontal force was forward (assistive) for different crutch tips.

between the crutch tip and the crutch bar. After attaching this crutch tip to the crutch bar, the crutch tip seemed to be loose due the plastic sliding on the crutch shaft. As a result, it tended to turn a little during the experiments and this could have affected the results.

As it was stated, the standard tip has a very small backward rotation angle that makes it more resistive during crutch stance motion. As a result, the standard tip will have larger negative horizontal forces with a smaller percentage of positive (forward) forces. In contrast, KCTs have greater rotation angles that can augment the positive portion of horizontal forces. Four of the Kinetic Crutch Tips had better results than standard tip.

V. CONCLUSIONS

In this research the effect of the design and hardness of Kinetic Crutch Tips on the crutch gait cycle were studied. This study included the calculation of maximum backward rotation angle that the crutch was able to move forward without any external forces. By using a mechanism for releasing a crutch, the effect of human characteristics were eliminated. This elimination helped us to directly compare the effect of crutch tips' kinetic profile on crutch movements. It was shown that a kinetic crutch tip is able to move forward with a negative angle of 3.64 deg while a standard tip can only move forward with a negative rotation angle of 1.23 deg. This augment in the backward rotation angle was caused due to the surface kinetic shape of KCTs and confirms an improvement in the assistive forward forces of the crutch.

In the second experiment, the step length, step time, and percentage of positive horizontal forces over all the eight subject for seven crutch tip were studied. The results showed an increase in ratio of positive horizontal forces for four of the Kinetic Crutch Tips. Positive (forward) horizontal forces are assistive during movement while negative (backward) ones are resistive. The increase in the percentage indicates that the augment in backward rotation angle for KCTs has caused the forward (assistive) horizontal forces to increase.

TABLE II
PERCENTAGE OF FORWARD (ASSISTIVE) HORIZONTAL FORCE FOR DIFFERENT CRUTCH TIP

Crutch Tip	Positive Horizontal Force (%)
Standard	55.6
3D	52.25
MD9	55.7
ME5	54.85
MF3	55.63
MG7	60.62
KCT	61.39

The effect of KCTs on energy level can be studied in the next step. Further study will be able to prove if the increase of assistive forces will cause the cost of walking and total input energy to decrease. These changes could have a prominent effect on the efficiency of walking.

Future experiments can evaluate more parameters on chronically crutch users regarding energy cost of walking such as Metabolic Equivalent of Task during stance and swing phase.

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REFERENCES

[1] W. Loebl and J. Nunn, "Staffs as walking aids in ancient egypt and palestine," *Journal of the Royal Society of Medicine*, vol. 90, no. 8, pp. 450–454, 1997.

[2] S. Epstein, "Art, history and the crutch." *Clinical Orthopaedics and Related Research*, vol. 89, pp. 4–9, 1972.

[3] J. S. Rovick, "Kinematic and pendular aspects of swing-through paraplegic crutch ambulation," Ph.D. dissertation, Northwestern University, 1982.

[4] E. Schlick, "Walking-stick." Oct. 23 1917, uS Patent 1,244,249.

[5] W. S. Monte, "Foot support crutch," Sep. 29 1981, uS Patent 4,291,715.

[6] D. Shortell, J. Kucer, W. L. Neely, and M. LeBlanc, "The design of a compliant composite crutch," *Journal of rehabilitation research and development*, vol. 38, no. 1, p. 23, 2001.

[7] L. W. Hoover, "Crutch with power lift and foot and method of using same," Feb. 1 1994, uS Patent 5,282,486.

[8] G. R. Farnham, "Power actuated crutch," Nov. 17 1964, uS Patent 3,157,189. [Online]. Available: https://www.google.com/patents/US3157189

[9] G. Farnham, "Hydraulically actuated crutch," Nov. 17 1964, uS Patent 3,157,188. [Online]. Available: https://www.google.com/patents/US3157188

[10] I. Handzic and K. B.Reed, "Kinetic shapes: Analysis, verification, and applications," *ASME Journal of Mechanical Design*, 2014.

[11] C. Joll, "An improved crutch." *The Lancet*, vol. 189, no. 4884, p. 538, 1917.

[12] R. G. Hall, "A rolling crutch: Preliminary report," *Journal of the American Medical Association*, vol. 70, no. 10, pp. 666–668, 1918.

[13] J. Basford and H. Rhetta, "Clinical evaluation of the rocker bottom crutch," *Orthopedics*, vol. 13, no. 4, pp. 457–460, 1990.

[14] D. Nielsen, J. Harris, Y. Minton, N. Motley, J. Rowley, and C. Wadsworth, "Energy cost, exercise intensity, and gait efficiency of standard versus rocker-bottom axillary crutch walking." *Physical therapy*, vol. 70, no. 8, pp. 487–493, 1990.

[15] M. A. LeBlanc, L. E. Carlson, and T. Nauenberg, "A quantitative comparison of four experimental axillary crutches." *JPO: Journal of Prosthetics and Orthotics*, vol. 5, no. 1, pp. 40–48, 1993.

[16] R. Mullis and R. M. Dent, "Crutch length: Effect on energy cost and activity intensity in non–weight-bearing ambulation," *Archives of physical medicine and rehabilitation*, vol. 81, no. 5, pp. 569–572, 2000.

[17] J. Crosbie, E. Armstrong, and J. Kempson, "Is walking aid height critical?" *Australian Journal of Physiotherapy*, vol. 38, no. 4, pp. 261–266, 1992.

[18] D. Capecci, S. H. Kim, K. B. Reed, and I. Handžić, "Crutch tip for swing-through crutch walking control based on a kinetic shape," in *Rehabilitation Robotics (ICORR), 2015 IEEE International Conference on*. IEEE, 2015, pp. 612–617.