Biomechanical Evaluation of Crutch Design Variations

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Abstract

The purpose of the study is to evaluate variations in the forces and moments applied to both the axillary (armpit) pad and handgrip of standard axillary crutches. The modified axillary pad was tapered in the front rather than symmetric and the modified handgrip was angled to about 17° rather than horizontal. The crutches used could be fitted with the standard or novel versions of both the axillary pad and handgrip, permitting four different crutch configurations. Using a six-axis load cell built into one of the crutches, forces and centers of pressure were calculated at both the axillary pad and the handgrip for each configuration in ten subjects. The only significant difference found was in the location of the handgrip forces. The center of pressure on the modified handgrip was more central that the location on the standard handgrip suggesting a more uniform force distribution.

Introduction

It is important for people with disabilities to be able to comfortably use crutches. Standing and walking allow for improved growth of bone, improved circulation of blood, reduced bladder infections and reduced pressure lesions (Shortell, Kucer, Neeley, & LeBlanc, 2001). Crutch walking offers physiological and psychological advantages that a person cannot gain by sitting and using wheeled mobility. The use of crutches helps people with disabilities to be able to move around freely. However, conventional crutches can present numerous problems to the crutch user and therefore are sometimes a hindrance rather than a benefit.

Traditional axillary crutches transmit jarring forces to the wrists and shoulders and can cause injuries to the crutch user. Many crutch users suffer from a condition called crutch palsy which occurs when the outer edge of the crutch saddle damages nerves in the axilla. This can impair conduction in the damaged nerves and can lead to total or partial paralysis in some of the muscles of the arm and hand (Subramony, 1989). A patient can usually recover relatively quickly from this condition by discontinuing the use of crutches. However, there are also more serious complications resulting from prolonged axillary crutch use including formation of an aneurysm and axillary artery thrombosis (Poddar, Gitelis, Heydemann, & Piasecki, 1993). Also, conventional crutches are usually loud and crutch users sometimes feel uncomfortable with the loud noises as they are walking.

Crutches have been used for over 5,000 years and they have not changed much in that time (LeBlanc, Carlson, & Nauenberg, 1993). There have been many attempts in the last century to modify the design of the standard axillary crutch including the development of Canadian crutches which are a combination of axillary crutches and elbow crutches; spring-loaded crutches; and rocker-bottom crutches. However, the designs have not generated much interest nor have they been successfully marketed to crutch users. It is important to develop a more effective, safe, and comfortable crutch for crutch users.

The benefits of developing a more effective crutch are not limited to a specific group of people, but spread to many different groups. Crutches are used by many people including amputees, paraplegics, people with broken bones, people with torn ligaments and many others. With a biomechanically favorable crutch, long-term crutch users as well as short-term crutch users will be greatly helped. It will provide better mobility for them without the obstacles of conventional axillary crutches. There will be less discomfort and harsh forces on the hands and axilla.

Approximately twice as much energy is required to walk with crutches than to walk without assistance (Fisher & Patterson 1981). People with disabilities often do not want to expend so much energy on a daily basis just for walking. With a less demanding and more ergonomically effective crutch, this energy gap can be lessened and more people will want to use crutches instead of wheeled mobility because the effort of ambulation will not be as high.

The purpose of this study is to develop a refined design for a crutch that has a modified axillary pad and handgrip and to determine if this new crutch distributes the axillary pad and handgrip forces more evenly.

Literature Review

Literature was reviewed for the following topics: traditional crutches; complications of crutches; and modified crutch designs.

Traditional Crutches

Crutches and other walking aids have been used for over 5,000 years and in that time, they have not changed much (LeBlanc et al., 1993). Currently, the two basic designs of crutches that are prescribed to most patients are axillary crutches and elbow crutches.

Axillary Crutches. Axillary crutches are a type of crutch that have a handgrip as well as a pad that rests against the side of the body just under the armpit. This type of crutch is used mostly by temporary crutch users (Shortell et al., 2001). Sometimes people avoid axillary crutches because of potential problems that may arise from their use such as hand, arm, and axilla problems (LeBlanc et al., 1993).

A study by Sankarankutty, Stallard, and Rose (1979) found that while subjects of their study said that ambulation with axillary crutches was less tiring than ambulation with elbow crutches, the percentage increase in heart rate from resting rate was about 20% higher for ambulation with axillary crutches compared to ambulation with elbow crutches. The researchers hypothesized that the increase in heart rate from the axillary crutches might have been due to artificial stimulation of the heart due to the contact of the top of the axillary crutch with the thoracic cage (Sankarankutty et al., 1979).

Instead of measuring energy expenditure by comparing heart rate, a study by Dounis, Rose, Wilson, and Steventon (1980) compared the amount of oxygen uptake for axillary crutch and elbow crutch ambulation. They found that oxygen uptake was less for ambulation with axillary crutches than for ambulation with elbow crutches. They concluded that for their study, walking with axillary crutches required less energy than walking with elbow crutches. Additionally, the subjects of the study rated the use of three types of crutches according to an effort scale provided by the researchers. All of the subjects were in complete agreement that there was less effort exerted when using axillary crutches than when using elbow crutches (Dounis, Rose, Wilson, & Steventon, 1980). However, other studies have not found significant differences in energy expenditure when subjects used axillary and elbow crutches for walking. Dounis, Steventon and Wilson (1980) found no difference in energy expenditure between axillary and elbow crutches by comparing oxygen consumption. Similarly, Hall, J., Elvins, Burke, Ring, and Clarke (1991) found no differences between the heart rate of subjects when using axillary and elbow crutch designs for ambulation.

Elbow Crutches. Elbow crutches are also known as forearm crutches. Like axillary crutches, they have a handgrip, but elbow crutches only extend to the elbow. There is no bar under or near the axilla. This type of crutch is used mostly by permanent crutch users (Shortell et al., 2001). Without the bar under the axilla, there are no jarring forces there, but there are still forces at the hands and wrists. As mentioned in the previous section, there has been some evidence that elbow crutches require more energy expenditure than axillary crutches. In a perceived effort rating by subjects in a study using both types of crutches, all of the subjects said that ambulation with elbow crutches required more effort than ambulation with axillary crutches (Dounis, Rose, Wilson, & Steventon, 1980).

Complications of Crutches

Crutches have many physiological and psychological benefits to individuals who use them by allowing them to walk instead of using wheeled mobility to get around. However, even though walking with crutches has many benefits, it also has many drawbacks that sometimes hinder individuals from using them.

Body Forces. There are harsh forces on the body due to crutch walking with axillary crutches. Forces at the crutch tip are transferred directly to the hand and wrist and indirectly to the axilla (Pariziale & Daniels, 1989). Wilson and Gilbert (1982) determined that the two important forces acting on the body during crutch walking are the horizontal forces on the axilla and the total load on the hands. The study found that the whole body weight is supported by the hands along with additional inertial forces. However, the axilla only has horizontal forces acting on it. In Wilson and Gilbert's (1982) study, it was determined that the peak body horizontal forces at the axilla occurred at the apex of swing-through. A force plate was used to measure the ground reaction force at the crutch tip and a force transducer system was used to measure the horizontal crutch reaction force on the axilla. According to this study by Wilson and Gilbert (1982), the crutch user's hands support 1.1 to 3.4 times his/her body weight, and the axilla support a horizontal load of about 3 to 11% of his/her body weight.

A similar study by Goh, Toh, and Bose (1986) found somewhat different results. The study found that the peak force at the hand during crutch ambulation was 44.4% of body weight which was less than found in Wilson and Gilbert's (1982) study. Also, Goh et al. (1986) tested the differences in the axillary forces when the subjects used the crutches correctly and incorrectly. When the crutches were used correctly, the axillary load was about 5% of body weight, but when the crutches were used incorrectly, the load was about 34% of body weight.

When the subjects used the crutches correctly, the posterior upper strut of the crutch was subjected to tension while the anterior strut was in compression during crutch stance phase.

While the forces on the body are greatly increased at the axilla and hands, the forces are also increased on the supporting limb during ambulation with crutches. In the study, "Lower-limb vertical ground-reaction forces during crutch walking," Stallard, Sankarankutty, and Rose (1978) measured the ground reaction forces on the supporting limb during crutch walking with both axillary and elbow crutches. It monitored the forces when the subjects landed on one foot as well as when they landed on two feet. For all single-foot landings with both types of crutches, the average increase was 24.5% and for all both-feet landings with both types of crutches, the average increase was 35.1% as compared to landing during normal walking. A similar study by Stallard, Dounis, Major and Rose (1980) also found an increase on the supporting limb during ambulation. The study found increases in vertical ground reaction forces of about 16% as compared to normal walking. In contrast to the findings of these two studies, a study by Li, Armstrong, and Cipriani (2001), found no increase in ground reaction force on the supporting limb. However, the study did find that during partial weight bearing crutch gait, the stance phase decreased significantly on the affected limb and increased significantly on the supporting limb. The center of gravity was shifted toward the supporting limb side of the body (Li et al., 2001).

A study by Shoup, Fletcher, and Merrill (1974) consisted of a literature search and a displacement analysis of swing-through crutch gait in order to make recommendations for further crutch modifications. The researchers suggested three developments in crutch design from the results of the study. They recommended that the vertical motion of the upper body be minimized, the shock absorption at the crutch tips be minimized, and the lateral motion of the crutch tips should be minimized.

<u>Medical Conditions.</u> Many cases of medical complications due to crutch walking have been documented. Crutch palsy is one of the least serious and is caused by axillary crutch walking (Raikin & Froimson, 1997). This can cause patients to have lesions of the radial and ulnar nerves which can cause denervation and conduction blocks along those nerves (Subramony, 1989). Crutch palsy can also lead to partial or total paralysis of muscles innervated by the radial, median and ulnar nerves as seen in a case report by Poddar et al. (1993). In the report, electromyography found radial nerve dysfunction with denervation of the radial innervated muscles. The study by Raikin & Froimson (1997) suggests that patients can expect complete recovery once they discontinue the use of the crutches and have splinting as required.

Another condition that can be induced by crutch use is acne mechanica. Acne mechanica is when pressure, friction, or rubbing provoke acne lesions (Kang et al., 1999). Kang et al. (1999) presented a case where a long-time crutch user developed this condition.

A more serious condition is the formation of an aneurysm due to the rubbing of the axillary pad of the crutch on the axilla of the user. There have been a number of documented cases of aneurysms caused by axillary crutch use and three are presented in the case study by Feldman, Vujic, McKay, Callcott, and Uflacker (1995). In a case report presented by Thomas and Deshmukh (1973), the patient suffered from an aneurysm of the brachial artery which led to complete thrombosis. The patient had to undergo immediate surgery and a graft was used to bridge the gap in the artery.

Modified Crutch Designs

Canadian Crutches. There is a basic design of the axillary crutch, but there has also been the development of a slightly modified version called the Canadian crutch. The Canadian crutch is basically a "Cuff" crutch that integrates aspects of axillary and elbow crutches. It has a handle as well as a "cuff" that wraps around the shoulder (Stallard, Sankarankutty, & Rose, "A Comparison," 1978). The cuff is designed to try to limit the amount of forces transmitted to the axilla during crutch walking. Since the design of the Canadian crutch is so similar to the traditional axillary crutch, it is sometimes put under the axillary crutch category (Hall J. et al., 1991).

In the study "A Comparison of Axillary, Elbow, and Canadian Crutches," Stallard, Sankarankutty, and Rose (1978) compared the heart rates of participants when using axillary, elbow, and Canadian crutches for ambulation. The study found that the Canadian crutch either gave the lowest heart rates at speeds comparable to those on the other types of crutches, or the highest speeds at heart rates comparable to those on the other types of crutches. Overall, the Canadian crutches appeared to be less energy consuming than the axillary and elbow crutches. A related study by Sankarankutty, Stallard, and Rose (1979) found similar results. The study found that the increase of heart rate for ambulation with Canadian crutches was about 20% lower than the increase of heart rate for ambulation with elbow crutches and about 40% lower than the increase of heart rate for ambulation with axillary crutches.

A study by Dounis, Steventon, and Wilson (1980) compared the energy use of subjects using elbow crutches and Canadian crutches by using a portable oxygen meter called the Oxylog. The results suggest that Canadian crutches are more efficient than elbow crutches because Canadian crutches allow a greater walking distance per unit of energy expenditure. While this study only contained five subjects, a follow-up study with ten subjects obtained similar results (Dounis, Rose, Wilson, & Steventon, 1980). This study compared axillary, elbow, and Canadian crutches. The study strongly suggests that Canadian crutches are preferred to both axillary and elbow crutches both objectively and subjectively.

Rocker-Bottom Crutches. The idea of the rocker-bottom crutch goes back for almost 90 years. In 1918, Hall R. developed and built a modified crutch design which featured a metal rocker at the base of the crutch. He replicated the shoulder curve of the crutch as it rotates during ambulation, and applied the arc in the form of a metal rocker to the base of the crutch. While Hall, R. (1918) described some of the advantages and disadvantages of the crutch design, no experimental study was included in his paper. However, the rocker-bottom crutch did not disappear after Hall's preliminary design. In a study by LeBlanc et al. (1993), a quantitative comparison of different axillary crutches was conducted. One of the crutches used in the study was a rocker-bottom crutch. It was essentially a modified modern version of Hall's rolling crutch. Similar to what Hall, R. (1918) described in his paper, LeBlanc et al. (1993) found that the crutch provided a smooth gait and increased stride length. However the disadvantages of the crutch were that it was awkward because of its size on stairs and aisles, it was heavy, and it was hard to stabilize (Hall, R., 1918; LeBlanc et al., 1993).

Basford, Rhetta, and Schleusner (1990) wanted to determine differences between rocker bottom crutches and traditional axillary crutches in speed of ambulation, number of steps, heart rates and patient security. Even though the study found no significant differences between any of the above, it found that the subjects preferred the axillary crutches to the rocker-bottom crutches. A similar study by Nielson et al. (1990) found a subjective preference for the standard axillary crutch for going up and down stairs, overall safety, and long-term use. This study also found no differences in walking performance including self-selected walking velocity, stride length, energy cost, gait efficiency, and relative exercise intensity.

Spring-loaded Crutches. The basis of spring-loaded crutches is that the extension post of standard crutches is replaced by a post with a spring mechanism in it (Pariziale & Daniels, 1989). In a study by Pariziale and Daniels, a basic design of a spring-loaded axillary crutch was compared to a standard axillary crutch. According to the findings of the study, the spring-loaded crutches reduced both the shock and maximum load at the hand and wrist when compared to traditional axillary crutches. There was a reduction of 20-25% in the stress put on the user's wrists. In a study by LeBlanc et al. (1993) that compared spring-loaded crutches to four other modified crutch designs, advantages and disadvantages were listed. The advantages were that the crutches had a lively feel, absorbed shock, and had energy return. The disadvantages found were the moving parts, the lack of rigidity, and the difficulty in ground clearance during swing-through.

Another, more recent, attempt to design a new crutch was undertaken by Shortell et al. (2001). This new elbow crutch was made of carbon fiber composite material which incorporated a spring mechanism directly into the body of the crutch. Instead of an actual spring, the researchers chose an S-curve design in which the two arcs of the S would deflect and act like a spring. Participants in the study were satisfied with the design, but felt that there was instability due to the movement in the crutch handle (Shortell et al., 2001).

Handgrip Modifications. Complications of nerve impingement and callous formations during crutch use can be attributed to the angle of the handgrip and the contour of the wooden handle (Yeakel & Margetis, 1969). The wrist naturally should be in slight ulnar deviation as opposed to radial deviation as it is during axillary crutch walking. A study by Yeakel and Margetis (1969) suggests that these problems can be eliminated with the use of poly (methyl methacrylate), a denture base repair resin. The material is putty-like so it can be molded to the hand of the specific crutch user. The study suggests that this allows the hand and wrist to be in their best structural alignment and that the handgrip distributes the body weight over the entire palm of the hand.

An article by Park, Malone, and Steglich (1952) argues for use of a tilted crutch handpiece. The researchers explain that when 35 people grasped free rod, the angle found was in a range from 5 to 30 degrees to the horizontal and that 73% of those ranged from 20-25%. Wiley (1960) also suggests that similar modifications should be made to the handgrip in axillary crutches by making it sloping to an angle of 15 degrees with the horizontal. He says that patients who have used this angled handgrip feel that it is more comfortable than when the grip is at its traditional horizontal position. Powers and Flatt (1962) suggest that further modifications should be made to the crutch handle in addition to the sloping handgrip. The researchers suggest that the diameter of the handgrip should be made larger and should be tapered near the little finger to allow for the different degrees of flexion of the digits. The increased diameter allows for a better power grip of the handle by the crutch user (Powers & Flatt).

Other Crutch Designs. Other designs of crutches exist and some studies have compared them to traditional designs of crutches. In a study by Hinton and Cullen (1982), traditional axillary crutches were compared to Ortho crutches. The Ortho crutches were made of aluminum with single uprights instead of double uprights like those found in traditional axillary crutches. The researchers suggested that for walking over a short distance, the Ortho crutch would be less tiring for an inexperienced patient than axillary crutches.

A report done by Nova and Laura (1985) described various modifications in walking aids. One of the aids described was the IMA crutch which featured a deformable underarm support and handgrip, full contact between crutch tip and the ground for any position of the crutch, and a button that released the upper portion of the crutch. The researchers state that unlike a normal axillary pad, the pad of the IMA crutch deflects when loaded. The telescoping aspect of the crutch allows the crutch to be reduced to a shorter length when the user is sitting (Nova & Laura). However, the study provides no scientific testing of the crutch design.

Wagstaff (1984) introduced a new design for a crutch called the Dublin crutch that featured a single shaft with a protruding handgrip and slightly modified axillary pad. The study found that there was a slight significant decrease in energy expenditure when walking with the Dublin crutch than when walking with a conventional axillary crutch.

Methods

This study evaluated whether or not there were differences in the forces and points of application of the forces on the axillary pads and handgrips. Data about the forces and the moments of force on the crutch were collected in 29 Recreation Building, the Biomechanics Laboratory.

A pair of Guardian Red Dot crutches fitted for individuals between 61 and 69 inches were used in this study. Additional axillary pads and handgrips were designed and constructed in the laboratory. The modified axillary pads were made of wood and were adapted from the shape of the original pad. The front end of the pad was tapered to reduce the pressure on the front of the axilla. Both the standard and the modified axillary pads are shown in Figure 1. The modified handgrips were made of wood and were angled to 17˚ which allowed for increased ulnar deviation. Both the crutch handles are shown in Figure 2. The crutches were adjustable to the two types of axillary pads and the two types of handgrips. This allowed for four configurations of the crutches. The left crutch was also modified to accommodate a six-axis load cell made by Sandia National Laboratories. Only three load cell readings were used in this study: F_x (force in x-direction), F_y (force in y direction) and M_z (moment about z-axis). Figure 3 shows how the load cell was incorporated into the crutch. Figure 4 shows the whole left crutch with the load cell built into it. Figure 5 shows a sketch of the crutch with the forces and locations shown as well as the coordinate system used.

Eight healthy subjects with no known musculoskeletal problems between the ages of 19-24 were used in the study. None of the subjects in the study needed any type of assistance for ambulation. Each subject came into the Biomechanics Laboratory once and the session lasted less than one hour. All the subjects signed Informed Consent forms prior to their participation in the study. Each subject was given instructions on how to walk with the crutches using a swing-through gait pattern. The subjects were explained that most of their body weight should be on the hands and not the axilla during swing-through.

For each of the four crutch configurations, each subject was given a five minute practice session or as long as needed to feel comfortable with the crutches around the laboratory. After the practice session, the subject was given a two minute rest period or as long as needed to feel adequately rested. The subject then performed three good trials with each crutch configuration by walking over the force plate with a swing-through crutch gait. A trial was considered good if the left crutch tip struck the force plate and the subject adequately cleared the force plate.

The force plate used was a Kistler Company force plate. The Motion Analysis System used was the Eagle System made by Motion Analysis Corporation.

Figure 1: Standard (left) and modified (right) axillary pads

Figure 2: Standard (top) and modified (bottom) handgrips

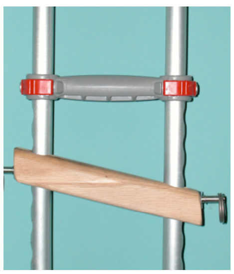


Figure 3: Load cell incorporated into left crutch

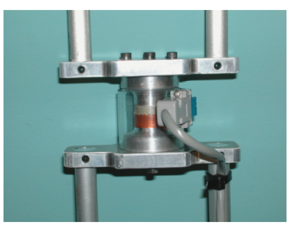


Figure 4: Complete left crutch with load cell built into it

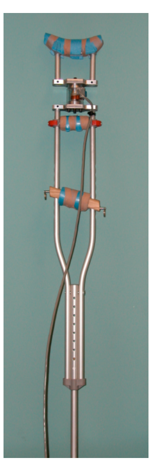
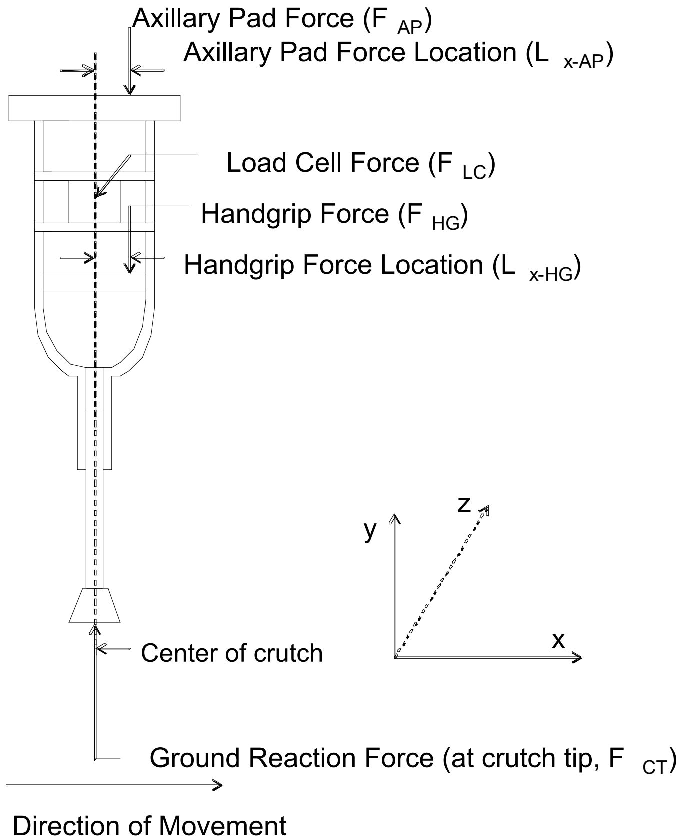


Figure 5: Sketch of crutch with forces and locations



From the forces and moments at the load cell (Fx, Fy, Mz) and the ground reaction forces when the crutch was at its vertical position, the forces and locations of the resultant forces at the handgrip and axillary pad were calculated using the equation F = ma. Figure 4 shows the forces and the locations on the crutch. The location is given in mm from the center of the crutch. All locations found were positive referring to the front half of the crutch. The forces and locations were found by putting the equations into a program in MATLAB. The program was run once for each subject and the forces and locations at the handgrip and axillary pad were calcuated.

The three equations used for the forces at the handgrip were:

1) $F_{HGx} + F_{LCx} + F_{CTx} = 0$
2) $F_{HGy} + F_{LCy} + F_{CTy} = 0$
3) $M_{LCz} + M_{CTz} + L_{x\text{-}HG}\_F_{HGy} + L_{y\text{-}HG}\_F_{HGx} = 0$

Assuming:

$a = 0$

$F_{HGz} = 0$

$M_{HGz} = 0$

The three equations used for the forces at the axillary pad were:

1) $F_{APx} + F_{LCx} = 0$
2) $F_{APy} + F_{LCy} = 0$
3) $M_{LCz} + L_{x\text{-}AP}\_F_{APy} + L_{y\text{-}AP}\_F_{Apx} = 0$

Assuming:

$a = 0$

$F_{APz} = 0$

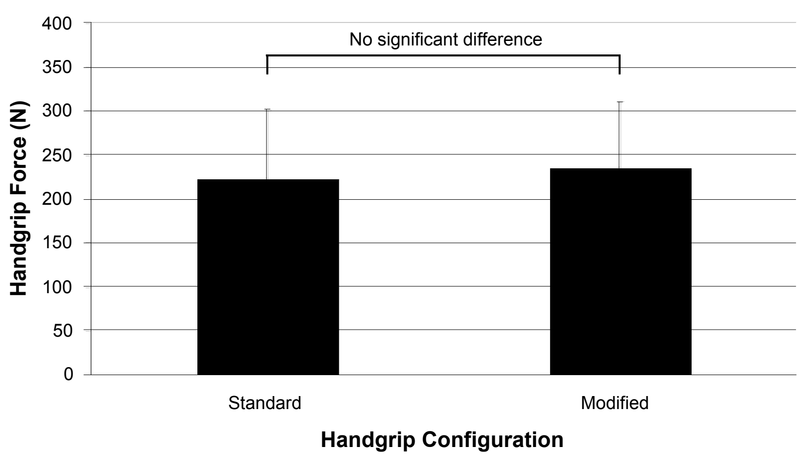
$M_{APz} = 0$

A two-way Analysis of Variance (ANOVA) with repeated measures was used to analyze the effects of handgrip (standard and modified) and axillary pad (standard and modified). A p-value of less than 0.05 was considered significant. The factors were the axillary pad and the handgrip. The levels for each were standard and modified.

Results

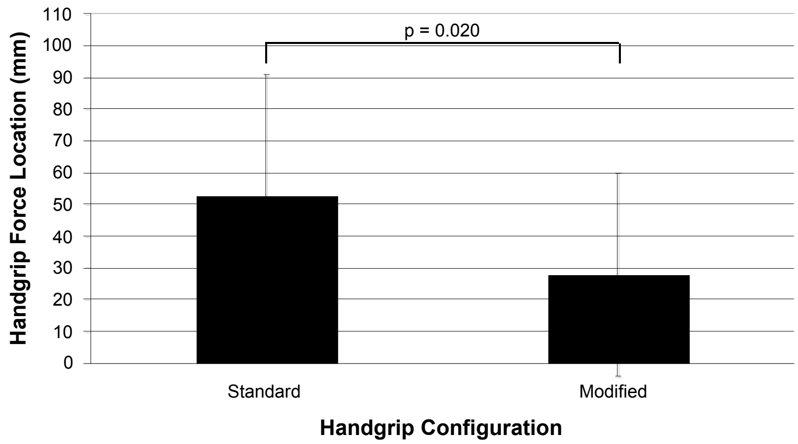
The only significant difference found was in the locations of the force for the handgrip designs. The forces on the handgrip and the forces and locations on the axillary pad were not significant.

Figure 6: Forces on the standard and modified handgrips



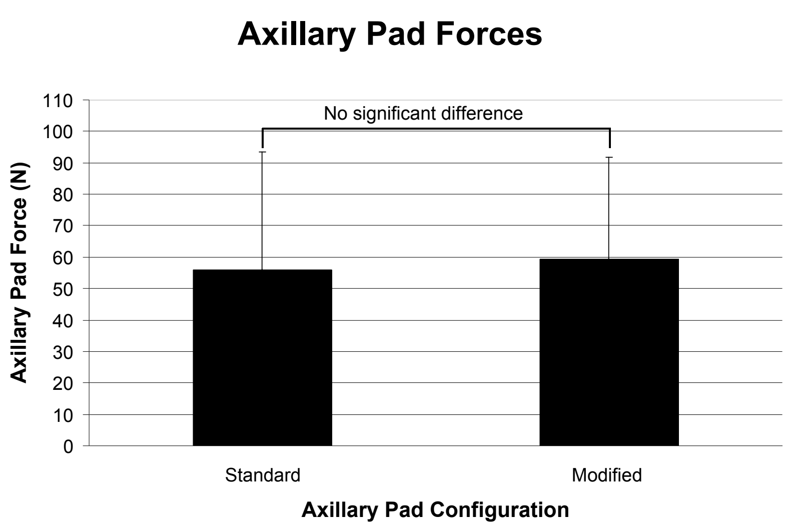
There was no significant difference found in the forces on the standard and modified handgrip designs ($p = 0.471$).

Figure 7: Force Locations for the standard and modified handgrips



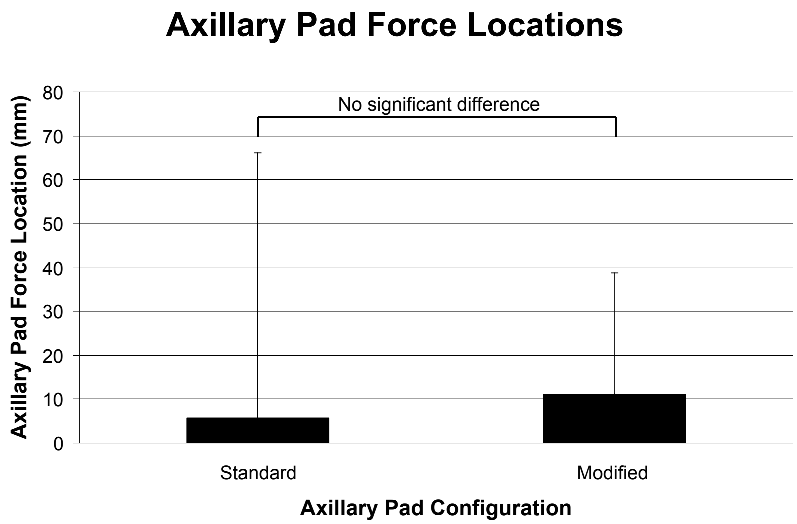
There was a signficant difference found in the force location on the standard and modified handgrip designs (p = 0.020). The average standard handgrip force location was 52.9mm from the center of the crutch. The average modified handgrip force location was 27.9mm from the center of the crutch.

Figure 8: Forces on the standard and modified axillary pads



There was no significant difference found in the forces on the standard and modified axillary pad designs (p= 0.434).

Figure 9: Force Locations for the standard and modified handgrips



There was no significant difference found in the force location on the standard and modified axillary pad designs ($p = 0.699$).

The subjects were asked to rate the comfort level of the each of the crutch configurations. Five of the eight subjects preferred both the standard handgrip and axillary pad. The main reason cited for preferring the standard handgrip over the modified handgrip was that the modified handgrip was larger and harder to grip.

Discussion

The point of application of the resultant handgrip force is closer to the center of the handgrip for the modified design than for the standard design. Since the force location is closer to the center of the crutch, this suggests that the body weight is distributed more evenly on the hand as predicted. For the standard design, the resultant force is applied much more to the front of the hand. This suggests that the forces are not distributed evenly in this configuration. For long-term crutch users, using this modified design for the handgrip may help to lower the jarring forces on the hand by the crutch handle. The angled handgrip design can potentially provide more comfort to crutch users by distributing the forces along the hand instead of concentrating the forces on only the front of the hand.

Five of the eight subjects preferred both the standard handgrip and axillary pad designs. However, since the main reason given for preferring the standard handgrip was that it was smaller and easier to hold, the angled shape of the modified handgrip may not have been taken much into account. The study aimed to compare the shapes of the two handgrips, but the comfort to the subjects may have relied more heavily on the size rather than the shape.

The sample size of eight people that was used for the study was very limited and was not able to be used to make generalizations for all crutch users. The subjects who participated in the study are all from the State College, PA area and therefore are not representative of the whole population. The demographics of State College may not be similar to the demographics of the whole population. If more subjects had been used, then perhaps more significant difference may have been detected in the forces at the handgrip and forces and locations at the axillary pad. However, the differences found were so slight that hundreds of subjects may have been needed to detect any real significant difference.

Additionally, the subjects that were used were healthy college-age people. The data for the subjects may not be representative of actual crutch users because the subjects in the study did not have any problems with ambulation. The swing-through portion of the gait cycle of the subjects will be considerably different from the swing-through portion of many crutch users because many crutch users wear immobilizing leg casts. Those crutch users need extra room for the straightened leg to clear the ground. Two of the participants were experienced crutch users so their ambulation with the crutches was likely more efficient than the rest of the participants who did not have as much practice with crutches. Some of the data may not have been representative of what would have been found by using experienced or long-term crutch users.

The leading cause of non-traumatic lower-leg amputation is diabetes mellitus (Mathur & Shiel, 2004). According to Mathur & Shiel (2004), recent information estimates that 13 million people in the United States have diabetes. Many diabetics are overweight or obese and therefore crutch dynamics for those individuals may be different than the crutch dynamics of healthy subjects. None of the subjects used in the study were obese and therefore they may not have tested these crutch biomechanics.

In future studies, the modified designs for both the standard and modified handgrips and axillary pads should be made from the same material and should be the same size when comparing the shapes alone. Also, using only experienced crutch users or giving inexperienced crutch users more practice time would help to make sure that all the subjects were walking as efficiently as possible. The energy expenditure of the subjects using each of the crutch configurations was not measured in this study. However, the extra energy required for crutch ambulation is a large hindrance to many crutch users. It is one of the main reasons why many disabled people choose wheeled mobility instead of using crutches. Comparing the energy expenditure between the four combinations would be another good indication of the efficiency of the designs. Also, further modifications besides simply changing the handgrip and axillary pads would be good to explore. For example, adding a spring to the bottom of the crutch in hopes to absorb some of the shock might also produce more significant results in the future. Also, testing different handgrip and axillary pad shapes than those used in this study would also be helpful.

While this study only found significance in the location of the handgrip forces, that information shows promise in reducing the jarring pressure at the hand. The information found in this study provides groundwork for future studies in the area of crutch dynamics.

References

Basford, J.R., Rhetta, M.L., & Schleusner, M.P. (1990). Clinical Evaluation of the Rocker Bottom Crutch. *Orthopedics, 13* (4), 457-450.

Dounis, E., Rose, G.K., Wilson, R.S.E., & Steventon, R.D. (1980). A Comparison of Efficiency of Three Types of Crutches Using Oxygen Consumption. *Rheumatology and Rehabilitation, 19,* 252-255.

Dounis, E., Steventon, R.D., & Wilson, R.S.E. (1980). The use of portable oxygen consumption meter (Oxylog) for assessing the efficiency of crutch walking. *Journal of Medical Engineering and Technology, 4*(6), 296-298.

Feldman, D.R., Vujic, I., McKay, D., Callcott, F., & Uflacker, R. (1995). Crutch-Induced Axillary Artery Injury. *Cardiovasc Intervent Radiol, 18*, 295-299.

Fisher, S.V., & Patterson, R.P. (1981). Energy Cost of Ambulation with Crutches. *Archives of Physical Medicine & Rehabilitation, 62,* 250-256.

Goh, J.C.H., Toh, S.L., & Bose K. Biomechanical study on axillary crutches during single-leg swing-through gait. *Prosthetics and Orthotics International, 10*, 89-95.

Hall, J., Elvins, D.M., Burke, S.J., Ring, E.F. J., & Clarke, A.K. (1991). Heart rate evaluation of axillary and elbow crutches. *Journal of Medical Engineering and Technology, 15*(6), 232-238.

Hall, R. (1918). A Rolling Crutch. *J.A.M.A., 70*, 666-668

Hinton, C.A., Cullen, K.E. (1982). Energy Expenditure During Ambulation with Ortho Crutches and Axillary Crutches. *Physical Therapy, 62*(6), 813-819.

Kang, Y.C., Choi, E.H., Hwang, S.m., Lee, W.S., Lee, S.H., & Ahn, S.K. (1999). Acne Mechanica Due to an Orthopedic Crutch. *Cutis, 64*, 97-98.

LeBlanc, M.A., Carlson, L.E., & Nauenberg, T. (1993). A Quantitative Comparison of Four Experimental Axillary Crutches. *Journal of Prosthetics and Orthotics, 5*(1), 20-28.

Li, S., Armstrong, C.W., & Cipriani, D. (2001). Three-Point Gait Crutch Walking: Variability in Ground Reaction Force During Weight Bearing. *Archives of Physical Medicine & Rehabilitation, 82*, 86-92.

Mathur, R., & Shiel, W.C. Jr. (June 2004). *Diabetes – David Meets Goliath.* Retrieved June 15, 2004, from http://www.medicinenet.com/script/main/art.asp?articlekey=17281

Nielsen, D.H., Harris, J.M., Minton, Y.M., Motley, N.S., Rowley, J.L, & Wadsworth, C.T. (1990). Energy Cost, Exercise Intensity, and Gait Efficiency of Standard Versus Rocker-Bottom Axillary Crutch Walking. *Physical Therapy, 70*(8), 487-493.

Nova, L.C., & Laura, P.A.A. Design and Use of Improved Walking Aids. (1985). *Journal of Biomedical Engineering, 7*, 329-333.

Pariziale, J., & Daniels J. (1989). The mechanical performance of ambulation using spring-loaded axillary crutches. *American Journal of Physical Medicine and Rehabilitation, 68*(4),193-195.

Park, H.W., Malone, E.W., & Steglich, R. (1952). The Tilted Crutch Handpiece. *Archives of Physical Medicine,* 731-733.

Poddar, S.B., Gitelis, S., Heydemann, P.T., & Piasecki, P. (1993). Bilateral predominant radial nerve crutch palsy. *Clinical Orthopaedics and Related Research. A Case Report, 297*, 245-6.

Powers, W.R., & Flatt A.E. (1962). Modified Crutch Handle. *Archives of Physical Medicine & Rehabilitation, 43,* 570-573.

Raikin, S., & Froimson, M. (1997). Bilateral Brachial Plexus Compressive Neuropathy (Crutch Palsy). *Journal of Orthopedic Trauma, 11*(2), 136-137.

Sankarankutty, M., Stallard, J., & Rose, G.K. (1979). The Relative Efficiency of 'Swing Through' Gait on Axillary, Elbow and Canadian Crutches Compared to Normal Walking. *Journal of Biomedical Engineering, 1*(1), 55-57.

Shortell, D., Kucer, J., Neeley, W.L., & LeBlanc, M. (2001). The design of a compliant composite crutch. *Journal of Rehabilitation Research and Development, 38*(1), 23-32.

Shoup, T.E., Fletcher, L.S., & Merrill, B.R. (1974). Biomechanics of Crutch Locomotion. *Journal of Biomechanics, 7*, 11-19.

Stallard, J., Dounis E., Major, R.E., & Rose, G.K. (1980). One Leg Swing Through Gait Using Two Crutches. *Acta orthop. Scand., 51,* 71-77.

Stallard, J., Sankarankutty, M., & Rose, G.K. (1978). A Comparison of Axillary, Elbow, and Canadian Crutches. *Rheumatology and Rehabilitation, 17*, 237-239.

Stallard, J., Sankarankutty, M., & Rose, G.K. (1978). Lower-limb vertical ground-reaction forces during crutch walking. *Journal of Medical Engineering and Technology, 2*(4), 201-202.

Subramony, S.H. (1989). Electrophysiological findings in crutch palsy. *Electromyogr. clin. Neurophysiol., 29*(5), 281-285.

Thomas, J.M., & Deshmukh, N. (1973). Aneurysm of the Brachial Artery with Complete Thrombosis Caused by a Crutch. *The American Surgeon,* 389-399.

Wagstaff, P.S. (1984). The Energetics of Walking using Axillary Crutches and the Prototype of a New Design Termed the Dublin Crutch. *Physiotherapy, 70*(11), 422-424.

Wiley, B.C. (1960). Crutch with Sloping Handgrip. *J.A.M.A., 172*(7), 694-695.

Wilson, J.F., & Gilbert, J.A. (1982). Dynamic Body Forces on Axillary Crutch Walkers During Swing-Through Gait. *American Journal of Physical Medicine, 61*(2), 85-92.

Yeakel, M.H., & Margetis, P.M. (1969). A Customized Crutch Hand Grip. *The American Journal of Occupational Therapy, 23*(5), 410-412.