Elbow Moment and Forces at the Hands During Swing-Through Axillary Crutch Gait

MARC REISMAN,
RAY G. BURDETT,
SHELDON R. SIMON,
and CYNTHIA NORKIN

We investigated swing-through axillary crutch gait (nonweight bearing on the left lower extremity) to determine the effects of gait speed, crutch length, and handle position on the forces exerted at the hands and on the moments exerted about the elbow joints. Ten healthy subjects, skilled in swing-through crutch gait, walked 1) at three speeds using fitted crutches, 2) at a fixed speed with four different crutch lengths, and 3) at a fixed speed with four different handle positions. We collected ground reaction forces that exerted simultaneously on the right crutch and motion data with a force plate and three high-speed movie cameras. A biomechanical model was developed to calculate the forces exerted at the right hand and the moments exerted about the right elbow joint. Changing gait speed from slow to the normal gait of the subject showed statistically significant effects ($p < .05$) on the forces at the hand. When we changed crutch heights for the subjects, we found no significant effects on the forces at the subjects' hands. Changing handle position significantly affected the moment at the elbow. Increasing the elbow-flexion angle above 30 degrees by raising the crutch handle 1 to 2 in resulted in a 100 percent increase in elbow-extension moment. We found a correlation of .82 between actual average elbow-flexion angle and elbow-extension moment. Changing gait speed or crutch length did not affect elbow moment.

Key Words: Biomechanics, Crutches, Elbow joint, Gait.

Fitting axillary crutches for patients is a common procedure for physical therapists. The scientific basis for criteria used to adjust crutch length and handle position for a patient, however, has not been studied in detail. Standards proposed for measuring crutch length have included the following: 77 percent of the patient's height, 1 height minus 18 in, 2 height minus 16 in, 3 and one and one-half or one to two fingers below the axillary fold to a point 4 in 4, 5 or 8 in 6 from the side of the foot. Suggested standards for measuring hand-piece position have varied from designating specific joint placement of the elbow angle at 30 degrees of flexion 5, 7 to vague descriptions that the elbow should be slightly bent. 8, 9 None of these criteria has been based on scientific or biomechanical data.

Only recently have analytical studies of crutch gait been performed. McBeath et al compared energy requirements of crutch walking against normal gait. 10 They found that partial weight-bearing crutch gait required 33 percent more energy than normal gait, and that nonweight bearing crutch gait required 78 percent more energy. Peacock did a myographic analysis of swing-through crutch gait with still photographs. 11 He described an external flexion moment that acted around the elbow during crutch gait, which is balanced by an extension moment provided by the upper arm muscles, specifically the triceps brachii muscle. Wells found that the mechanical work during swing-through crutch walking was approximately the same as in normal walking but that more of this work was done by the upper extremities. 12 Because these muscles are not functionally designed for supporting the body's weight, they fatigued more rapidly than the lower extremity muscles. Shoup et al performed a biomechanical displacement analysis of a swing-through crutch gait to establish criteria for improving crutch design. 13 Shoup later used these criteria to develop a new type of forearm crutch for children. 14 Other investigators have measured the forces acting on crutches and other ambulatory aids. 15-17 Although these studies have looked at energy consumption in crutch walking and at the forces acting on the crutches, the forces that acted on the joints of the body have not been adequately examined. The wrist and elbow joints are heavily relied on for support during the swing-through phase of axillary crutch gait. Although joint forces at the wrist 18 and torque at the elbow have been measured for isometric contractions, 19-21 these forces have not been measured during crutch walking. The purpose of this study was to show that variation of speed, crutch length, and handle position would positively affect the forces exerted by the hands and the moment exerted by the elbow joint during nonweight-bearing axillary crutch walking.

Mr. Reisman is a staff member, Washington University, Department of Physical Therapy, Irene Walter Johnson Institute of Rehabilitation, St. Louis, MO 63110 (USA).

Dr. Burdett is Assistant Professor, Program in Physical Therapy, School of Health Related Professions, University of Pittsburgh, Pittsburgh, PA 15261.

Dr. Simon is Director, Gait Analysis Laboratory, Children's Hospital, Boston, MA 02115.

Ms. Norkin is Assistant Professor, Sargent College of Allied Health Professions, Boston University, Boston, MA 02215.

This article was submitted August 2, 1983; was with the authors for revision 38 weeks; and was accepted November 11, 1984.

* 1 in = 2.54 cm.
TABLE 1
Average Speed, Cadence, and Step Length of Crutch-Walking Trials

<table>
<thead>
<tr>
<th>Speed</th>
<th>Cadence</th>
<th>Step Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow</td>
<td>0.46 m/sec</td>
<td>60 steps/min</td>
</tr>
<tr>
<td>Normal</td>
<td>0.73 m/sec</td>
<td>72 steps/min</td>
</tr>
<tr>
<td>Fast</td>
<td>1.12 m/sec</td>
<td>88 steps/min</td>
</tr>
</tbody>
</table>

To determine the effects of speed, crutch length, and handle position on the forces at the hands and moments at the elbow, we asked each subject to walk with the crutches under 11 different conditions: 1) at the three different speeds, using crutches fitted according to the standard selected; 2) at the normal speed, using four different crutch lengths (longer by 2 in and by 1 in; shorter by 2 in and by 1 in), but with the handle position set so that a 30-degree flexion angle existed at the elbow; and 3) at the normal speed, using four different handle positions (higher by 2 in and 1 in; lower by 2 in and 1 in), but with the crutch length the same as the fitted condition.

Speed was controlled by controlling both cadence and step length. Cadence was set by a metronome, and step length was controlled by marks placed along the floor. The subjects were asked to place each step of the foot or crutch near the markers. A practice session was taken for each walk so that the subject could become familiar with each speed, crutch length, and handle position. The walks were initiated from specific spots on the floor so that the right crutch would land in the middle of a force plate after three strides.

**Method**

**Subjects**

Ten healthy women, randomly selected from a group of physical therapists and physical therapy students who had some skill in performing a swing-through crutch gait, were subjects in this study. Their average age was 27.6 years. To rule out height as a factor in measuring forces and moments, their heights were limited to a range of 63.5 to 66 in. None of the subjects reported any history of gait abnormalities. We used a form approved by Boston University and the Gait Analysis Laboratory of Children's Hospital to obtain informed consent from each subject. Approval for this study was received from the Human Subjects Committee of the University.

**Procedure**

For each gait session, the subjects wore shorts, t-shirts, and sneakers. To aid in identifying landmarks on film, small squares of black tape with white dots in the center were placed over the right acromion process, the right lateral epicondyle of the humerus, the dorsum of the right wrist midway between the ulnar and radial styloid processes, the right crutch tip, and the center of the axilla crossbar. The crutches used in this study were standard wooden axillary crutches with rubber-covered axilla crossbars, hand crossbars, and tips. Extra holes were drilled to allow for 1-in adjustments of the handles. A team of physical therapists at the Gait Analysis Laboratory decided the method for fitting the crutches based on commonly used criteria.3,5,7 Crutch length was measured in the following manner: The subject stood with her arm abducted to 90 degrees. The crutches were measured from a point 2 in below the axilla to a point 12 in lateral to the midline of the body on a line along the tips of the shoes. The handle position was adjusted to provide 30 degrees of elbow flexion. Two physical therapists independently measured the elbow angle by centering a standard 7-in plastic goniometer over the lateral condyle of the humerus and by using the acromion and radial styloid processes as references.

Crutch gait may involve full, partial, or nonweight-bearing status on the part of either leg. For the purposes of this study, swing-through axillary crutch gait was defined as a nonweight-bearing gait with the left foot off the ground. The right foot, therefore, supported all of the force not carried by the crutches. The "normal" average speed of crutch gait for a subject with this height was determined in a pretest to be 0.73 m/sec. We considered that speeds of 0.46 m/sec and 1.12 m/sec deviated enough from the normal to be considered fast and slow speeds. The cadences and step lengths to achieve these speeds were also determined from the pretest. Table 1 gives the gait speeds, cadences, and step lengths from this study.

**TABLE 2**
Average Normalized Force on Hands During Crutch Stance of Different Trials

<table>
<thead>
<tr>
<th>Speed</th>
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**Force and Motion Analysis**

The setup of the equipment, electronic systems, and computer programs for computing the elbow moment and the forces at the hands was developed at the Gait Analysis Laboratory and Children's Hospital, Medical Center, Boston. The body motion, in addition to ground reaction forces acting on the crutch tip in the vertical, anterior-posterior, and mediolateral directions, were collected simultaneously by an Advanced Mechanical Technology force platform† and by three high-speed Photosonics 16-mm movie cameras‡ positioned orthogonally on three sides of the walkway. The right and left cameras were 12 ft§ away from the center of the force plate, and the front camera was 29 ft away. After the films were developed, they were analyzed on a Vanguard Motion Analyzer|| with a Graf Pen Sonic Digitizer# to collect the two-dimensional coordinates of specific points on each film. The three-dimensional coordinates of the wrist, elbow, and shoulder joints; crutch tip; and center of the axilla crosspiece were then calculated from these two-dimensional coordinates. Simon et al have described this force and motion analysis system in more detail.22

† Advanced Mechanical Technology, Inc, 141 California St, Newton, MA 02158.
‡ Instrumentation Marketing Corp, 820 S Mariposa St, Burbank, CA 91506.
§ 1 ft = 0.3048 m.
|| Vanguard Instrument Co, Melville, NY 11747.
# Science Accessories Corp, Southport, CT 06490.
We developed a biomechanical model of crutch walking to calculate the forces acting on the hands and the moment exerted by the elbow extensors. The assumptions used in this model were 1) the mass and acceleration of the crutch, forearm, and hand could be neglected during crutch stance; 2) forces on the crutch occur only at the tip, handle, and crutch top; 3) the force at the crutch top is perpendicular to the sagittal plane; and 4) no twisting moments existed that were exerted on the crutch from the wrist (Figure).

By neglecting the mass and acceleration of the crutch during crutch stance, the forces acting on the crutch from the hand were calculated from Newton’s laws of equilibrium. The direction of the axis of the elbow joint was assumed to be perpendicular to a plane formed by the shoulder-, elbow-, and wrist-joint centers. This axis is not, in general, perpendicular to the sagittal plane during crutch walking. Therefore, the component of the resultant force within this plane was calculated. This force was multiplied by the perpendicular distance between the elbow-joint center and the action line of this component to get the external moment exerted by the crutch about the flexion-extension axis of the joint. By neglecting the mass and acceleration of the forearm during crutch stance, the internal moment exerted by the elbow extensors was equal to this external moment exerted by the crutch. The resultant force was divided by body weight and was averaged over the crutch-stance time to give the average resultant normalized force at the hands. Elbow-extension moments were normalized by dividing by body weight and forearm length and were averaged over either the crutch-stance phase or the entire gait cycle. We thought average force and average moment were better indicators of muscle effort than peak force or moment, which may be exerted for only an instant. The actual elbow angle at each instant in time during crutch stance was also calculated and was used to obtain the average angle of the elbow during crutch stance.

Data Analysis

Six analyses of variance (ANOVAs) with repeated measures were performed to determine the effect of gait speed, crutch length, and handle position on the resultant normalized force at the hand and on the normalized moment at the elbow. The significance level was set at \( p < .05 \). Individual comparisons of means were made when appropriate by using the Neuman-Keuls multiple comparison test. A Pearson product-moment correlation coefficient was used to determine the correlation between elbow torque and elbow-flexion moment.

RESULTS

Table 2 shows the average resultant force exerted on the crutch by the hands during crutch stance as a function of speed, crutch length, and handle position. Analysis of variance showed the following results. 1) There was a statistically significant difference \( (p < .05) \) between the average force exerted at the hands during slow walking and normal walking. This force difference, however, is only 3.8 percent of body weight smaller than the force at normal speed. Although statistically significant, this difference may not represent any valuable clinical difference. 2) We found no significant difference \( (p > .05) \) among the average force values as a function of crutch length or handle position.

The forces at the hand create moments at the elbow joint that must be balanced internally by the triceps brachii muscle acting on its lever arm. These normalized moments are shown in Table 3. The average elbow moment changed very little with walking speed and indicated that elbow-extension muscle effort did not vary much with speed of walking. The average elbow moment exerted during crutch stance also did not vary significantly with crutch length. We found a significant variation, however, in elbow moment with changes in handle position. The two higher handle positions resulted in about twice as much moment as the fitted position or the two lower positions.
TABLE 3
Average Normalized Elbow-Extension Moment During Crutch Stance (%)

<table>
<thead>
<tr>
<th>Speed</th>
<th>Slow (0.46 m/sec)</th>
<th>Normal (0.73 m/sec)</th>
<th>Fast (1.12 m/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.14</td>
<td>4.19</td>
<td>4.52</td>
</tr>
<tr>
<td>Crutch length</td>
<td>+2 in +1 in Fitted</td>
<td>-1 in -2 in</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.15</td>
<td>5.63</td>
<td>5.24 5.30</td>
</tr>
<tr>
<td>Handle position</td>
<td>+2 in +1 in Fitted</td>
<td>-1 in -2 in</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.20</td>
<td>8.12</td>
<td>4.19 4.51</td>
</tr>
</tbody>
</table>

The effect of changing handle positions on the elbow angle can also be seen in Table 4. At the fitted position, the elbow angle averaged 31 degrees among all the subjects before crutch walking. Raising the crutch handle resulted in an increased elbow angle of about 11 degrees per inch; lowering the handle resulted in a decrease in elbow flexion of about 8 or 9 degrees per inch. The actual, average flexion angle during crutch stance was, in general, much smaller than the angle measured before gait, but this difference was not as great for the fitted position and the lower handle positions. The correlation between actual, average elbow-flexion angle and elbow-extension moment was high (.82).

DISCUSSION

Several compensations that could account for the lack of significant differences in forces at the hands existed in this study. The shoulder girdle complex or the stance leg, through eccentric contractions, may absorb some of the energy caused by increases in speed or changes in crutch length or handle position. The shoulder girdle muscles may also help to keep the center of gravity at a relatively constant level during crutch stance, which would decrease forces on the crutches and on the hands. Another way that the center of gravity may be kept at a relatively constant level is by adjusting the abduction angle of the crutches from the body. When the crutches are long, they can be placed further from the body. All of the above occurred in this study.

The elbow-joint moment is the product of the force at the hands times the perpendicular distance from the elbow joint to the force (Figure). This perpendicular distance is a function of the elbow angle; in general, increasing the flexion angle will increase the perpendicular distance. The force at the hands was approximately the same for each crutch length and each gait speed, but the elbow angle was readjusted to 30 degrees of flexion after each length change. Therefore, the result of no significant difference in elbow moments with crutch-length changes and speed changes is not surprising. Energy consumption has been shown in other studies to increase with speed of crutch walking. The present study indicates this increase in energy is probably caused by increased effort by muscles crossing other joints, possibly the shoulder girdle muscles and the muscles of the stance leg, rather than the elbow-joint muscles.

The difference in elbow moment that occurred with changes in handle position is almost entirely caused by an increase in the lever-arm distance between the elbow joint and the action line of the force on the hands. For the three, lower handle positions, the actual elbow angles were very similar, even though the initial angles were different. As a result, the average extension moments were also very similar. At the higher handle positions, the subjects used much larger elbow flexion angles during gait, and, therefore, the elbow-joint moments were much larger also. By using some relatively quick and inexpensive method of measuring elbow angle during gait, such as videotape or electrogoniometry, the elbow-joint moment could be estimated from the strong linear relationship between actual elbow angle and joint moment without the use of a force platform.

Clinical Implications

The results of this study indicate that the 30-degree resting elbow-flexion angle often used for fitting axillary crutches has a good biomechanical basis. If a therapist is going to deviate from this standard, it should be in the direction of lowering the handle slightly to decrease elbow flexion. Crutches should be made with fine enough adjustments at the handle to allow for proper fitting because increments of 1 in can make significant differences in elbow moment. An increase in elbow moment may result in a significant increase in the amount of force that the elbow extensors must exert. Muscle fatigue may, therefore, become one of the limiting factors in crutch walking.

CONCLUSIONS

The force exerted at the hands did not vary greatly with crutch length, handle position, or speed of walking. The moment exerted at the elbow joint also did not vary with crutch length or speed, but handle position did have a significant effect on elbow-extension moment. Increasing the resting flexion angle above 30 degrees by raising the crutch handle 1 or 2 in resulted in increasing the elbow moment by almost 100 percent, but decreasing the elbow-flexion angle by lowering the crutch handle did not significantly change the elbow-extension moment. We also found a high positive correlation between average elbow angle and elbow-extension moment.

Elbow-extensor muscle strength and endurance is not the only physical factor that affects the ability of someone to use axillary crutches effectively. Other factors, such as shoulder girdle muscle strength, may be more critical. Further examination of the biomechanics of the shoulder joint during crutch gait may elucidate how forces are kept constant at the elbow and hand during moderate changes of crutch height, handle height, and gait speed.

TABLE 4
Effect of Crutch Handle Position on Elbow Angle and Moment

<table>
<thead>
<tr>
<th>Position</th>
<th>Flexion Angle (%)</th>
<th>Extension Moment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pregait (X)</td>
<td>During Gait (X)</td>
</tr>
<tr>
<td>2 in high</td>
<td>53 26</td>
<td></td>
</tr>
<tr>
<td>1 in high</td>
<td>42 23</td>
<td></td>
</tr>
<tr>
<td>Fitted</td>
<td>31 16</td>
<td></td>
</tr>
<tr>
<td>1 in low</td>
<td>22 13</td>
<td></td>
</tr>
<tr>
<td>2 in low</td>
<td>14 11</td>
<td></td>
</tr>
</tbody>
</table>
REFERENCES

1. Determining the length of crutches. Modern Hospital 15:332, 1920
5. Deaver GG: What every physician should know about the teaching of crutch walking. JAMA 142:470-472, 1950