A Kinematic Comparison of Spring-Loaded and Traditional Crutches

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Context: A novel spring-loaded-crutch design may provide patients additional forward velocity, relative to traditional axillary crutches; however, this idea has not yet been evaluated. Objective: To quantify elastic potential energy stored by spring-loaded crutches during crutch-ground contact and determine whether this energy increases forward velocity for patients during crutch ambulation. Because elastic potential energy is likely stored by the spring-loaded crutch during ambulation, the authors hypothesized that subjects would exhibit greater peak instantaneous forward velocity during crutch-ground contact and increased preferred ambulation speed during spring-loaded-crutch ambulation, relative to traditional-crutch ambulation. Design: Within-subject. Setting: Biomechanics laboratory. Participants: 10 healthy men and 10 healthy women. Interventions: The independent variable was crutch type: Subjects used spring-loaded and traditional axillary crutches to ambulate at standardized and preferred speeds. Main Outcome Measures: The primary dependent variables were peak instantaneous forward velocity and preferred ambulation speed; these variables were quantified using high-speed videography and an optoelectronic timing device, respectively. Between-crutches differences for the dependent variables were evaluated using paired t tests (α = .05). Elastic potential energy stored by the spring-loaded crutches during crutch-ground contact was also quantified via videography. Results: Peak forward velocity during crutch-ground contact was 5% greater (P < .001) for spring-loaded-crutch ambulation than for traditional-crutch ambulation. Preferred ambulation speed, however, did not significantly differ (P = .538) between crutch types. The spring-loaded crutches stored an average of 2.50 ± 1.96 J of elastic potential energy during crutch-ground contact. Conclusions: The spring-loaded crutches appear to have provided subjects with additional peak instantaneous forward velocity. This increased velocity, however, was relatively small and did not increase preferred ambulation speed.

Keywords: rehabilitation, biomechanics, mechanical energy, gait speed

Humans have used crutches to overcome gait impairments for thousands of years, and it has been reported that approximately 600,000 Americans use crutches each year. Although crutch design has evolved over time, traditional...
Spring-loaded crutches alter the reaction forces transmitted to the upper extremities in a way that presumably decreases the risk of upper extremity pathology during traditional-axillary-crutch use. Spring-loaded crutches that contain one or more springs in the crutch post may also facilitate forward motion by storing and releasing mechanical energy during crutch ambulation. The springs compress, storing elastic potential energy during crutch–ground contact, and then decompress, converting stored elastic potential energy into kinetic and gravitational potential energy. Theoretically, if this kinetic energy is efficiently transmitted to the patient’s center of mass, forward velocity of the center of mass may be increased. This type of energy storage is similar to the manner in which humans and other mammals store elastic potential energy in stretched tendons and then convert that stored energy into kinetic energy during walking and running. Some mechanical characteristics of spring-loaded-crutch ambulation have been previously described; however, a quantitative description of elastic potential energy that is stored and converted into kinetic energy during spring-loaded-crutch ambulation, and its effect on forward motion, has not yet been reported.

Two manufacturers (Millennial Medical Inc, Logan, UT, USA, and Donjoy Inc, Vista, CA, USA) are currently marketing an identical spring-loaded-crutch design (Figure 1). These manufacturers claim that this crutch design stores and returns mechanical energy to the patient, helping the patient move forward. This claim, however, has not yet been objectively evaluated. The purpose of this study was to investigate this claim. To accomplish this purpose, we quantified the elastic potential energy that was stored by the spring-loaded crutches during the crutch–ground contact phase of crutch ambulation and peak instantaneous forward velocity for the whole-body center of mass immediately after decompression of the crutch spring. We then compared this peak instantaneous forward velocity with that at a comparable time during traditional-crutch ambulation. We also compared preferred ambulation speed between spring-loaded- and traditional-crutch ambulation. We hypothesized that, because of elastic potential energy that is stored by the spring-loaded crutch, peak instantaneous forward velocity and preferred ambulation speed would be greater for spring-loaded-crutch ambulation than for traditional-crutch ambulation.

Methods

Participants

Twenty healthy subjects (10 women, 10 men; age 23 ± 2 years, height 1.73 ± 0.10 m, mass 69.2 ± 13.7 kg) gave informed consent and participated in this study. Male subjects wore footwear and spandex shorts. Female subjects wore footwear, spandex shorts, and sports bras.
A within-subject design was used. Each subject used both the traditional- and spring-loaded crutches to ambulate, in a randomized order. Crutch design was the independent variable. The primary dependent variables were peak instantaneous forward velocity of the whole-body center of mass during crutch–ground contact and preferred ambulation speed. Elastic potential energy that was stored by the spring-loaded crutch during crutch–ground contact was also quantified.

**Procedures**

The specific spring-loaded crutch that was tested during this study was the In Motion Pro (Millennial Medical Inc; Figure 1). Spring-loaded and traditional crutches were fit to subjects using accepted methods. To ensure that subjects were comfortable with both crutch types, they ambulated 100 m with each type of crutch before data collection. They were then asked whether they felt comfortable using each crutch type. All responded affirmatively to this question after the 100-m familiarization
session. Three-point crutch ambulation, with the dominant leg contacting the ground, was performed for all trials. The dominant leg was identified as the leg that would be used to kick a soccer ball. Next, 35 reflective markers were applied to various anatomical landmarks in accordance with the VICON Plug-In Gait marker arrangement (Figure 2). This arrangement has been shown to accurately facilitate calculation of whole-body center-of-mass position. To monitor crutch motion, reflective markers were also attached to the crutches (Figure 1). For the spring-loaded crutches, a reflective marker was applied distal and proximal to the spring, to quantify spring deformation (Figure 1). Whole-body center-of-mass calculations did not include the mass of the crutches.

Subjects first performed 3 preferred-speed trials with each crutch type and then performed 3 standardized-speed trials with each crutch type (0.97 m/s ± 5%). The standardized speed was used so that any between-crutches differences

Figure 2 — A depiction of the reflective marker arrangement (VICON Plug-in Gait) used in the current study.
in peak instantaneous forward velocity could not be attributed to differences in ambulation speed. During the standardized-speed trials, an optoelectronic timing device (Brower Timing Systems, Draper, UT, USA) was used to provide immediate feedback regarding ambulation speed to subjects. This same timing device was used to measure ambulation speed for the preferred-speed trials. Video data were collected (60 Hz; VICON, Centennial, CO, USA) for all trials. Three-dimensional coordinates describing each reflective marker’s position were tracked and digitally filtered using the Woltring filter in VICON Nexus 1.3 software.

The elastic potential energy that was stored by the spring-loaded crutch during crutch–ground contact was calculated using the collected coordinate data and a standard equation: elastic potential energy \( (J) = \frac{1}{2} \cdot k \cdot x^2 \), where \( k \) indicates spring stiffness (12.95 kN/m) as reported by the manufacturer and \( x \) indicates spring deformation. Spring deformation was determined by quantifying the change in distance between the 2 markers that were just proximal and distal to the spring during 2 different parts of crutch ambulation: immediately before crutch–ground contact and at maximal spring deformation. As measured in our laboratory, the spring-loaded-crutch design involved a compressive “preload” of 220 N on each spring (ie, although no external force was applied to the crutches, the springs were compressed with a compressive force of 220 N). This, however, did not alter the magnitude of energy that was stored by the crutch and available for return to the patient, because the springs always returned to the same original compressed position after crutch–ground contact.

Peak instantaneous forward velocity for the whole-body center of mass during crutch–ground contact was derived from the coordinate data using a central-differences approach. Across all subjects, for the spring-loaded-crutch trials, this peak velocity consistently occurred immediately after spring decompression, just before the end of crutch–ground contact. For the traditional-crutch trials, this peak also occurred consistently just before the end of crutch–ground contact. Elastic potential energy was averaged across the standardized-speed trials for the spring-loaded-crutch design for each subject. Peak instantaneous forward velocity was averaged across the standardized-speed trials for both crutch designs for each subject. Preferred ambulation speed was averaged across the preferred-speed trials for both crutch designs for each subject.

**Statistical Analyses**

We used paired \( t \) tests to compare sample means between the 2 crutch designs for peak instantaneous forward velocity for the whole-body center of mass during crutch–ground contact of the standardized-speed trials, ambulation speed during the standardized-speed trials (to ensure that speed was properly controlled for), and ambulation speed during the preferred-speed trials. Alpha was set at .05 for these comparisons and Bonferroni-adjusted for multiple comparisons. Because we assumed that the elastic potential energy stored by the traditional crutch was negligible, we did not compare elastic potential energy between crutch types. Means and standard deviations were used to describe elastic potential energy stored by the spring-loaded crutch.
Results

Sample means and standard deviations for both crutch types for peak instantaneous forward velocity, preferred ambulation speed, and standardized ambulation speed are presented in Table 1. Elastic potential energy for the spring-loaded crutch is also presented in Table 1. Peak instantaneous forward velocity was 5% greater \( (P < .001, t_{0.05,19} = -4.598) \) for spring-loaded-crutch ambulation than for traditional-crutch ambulation. Conversely, preferred ambulation speed did not significantly differ \( (P = .538, t_{0.05,19} = -0.618) \) between the spring-loaded and traditional crutches. As was expected, there were no between-crutches differences \( (P = .396, t_{0.05,19} = 0.868) \) for ambulation speed during the standardized-speed trials.

Discussion

The purpose of this study was to evaluate the idea that elastic potential energy is stored in a compressed spring and then transferred to patients on spring decompression, facilitating forward motion for patients using spring-loaded crutches. We tested a relatively novel spring-loaded crutch that is now being marketed for which manufacturers have put forth the aforementioned idea. The idea, however, had not yet been objectively evaluated. In accordance with manufacturer claims, we hypothesized that peak instantaneous forward velocity for the whole-body center of mass and preferred ambulation speed would be greater during spring-loaded-crutch ambulation than during traditional-crutch ambulation. The current data only partially confirmed these hypotheses. As was expected, the spring-loaded-crutch design stored elastic potential energy during crutch–ground contact, and peak instantaneous forward velocity was greater during spring-loaded-crutch ambulation than during traditional-crutch ambulation (Table 1). There was no difference, however, for preferred ambulation speed between spring-loaded- and traditional-crutch ambulation (Table 1).

We believe that the relatively small difference in peak instantaneous forward velocity is likely related to the additional mechanical energy that is transferred from the decompressing spring to the subject during the latter phases of crutch–ground contact. The lack of a between-crutches difference in preferred ambulation speed,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Spring-Loaded- and Traditional-Crutch Ambulation, Mean ± SD</th>
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<tbody>
<tr>
<td></td>
<td>Spring-loaded</td>
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<tr>
<td>Peak instantaneous forward velocity (m/s)*</td>
<td>1.29 ± 0.08</td>
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<tr>
<td>Preferred ambulation speed (m/s)</td>
<td>0.97 ± 0.10</td>
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<tr>
<td>Standardized ambulation speed (m/s)</td>
<td>0.96 ± 0.04</td>
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<tr>
<td>Elastic potential energy (J)</td>
<td>2.50 ± 1.96</td>
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Peak instantaneous forward velocity and elastic potential energy were measured during crutch–ground contact. The preferred and standardized ambulation speeds were maintained by subjects throughout the preferred- and standardized-speed trials, respectively. A significant difference in peak forward velocity, indicated by the asterisk, confirmed our hypothesis and indicated that spring-loaded crutches provide additional forward velocity. This additional velocity, however, failed to alter preferred ambulation speed.
However, was unexpected and is more difficult to explain. The lack of a difference for preferred ambulation speed implies that during spring-loaded-crutch ambulation, an increased peak velocity immediately after spring decompression was negated by a decreased velocity during another part of crutch ambulation. This decreased velocity may be related to mechanical energy required of the patient to compress the spring during initial crutch–ground contact. Although the spring may return energy to the patient at the end of crutch–ground contact, it appears to take energy from the patient during a different part of spring-loaded-crutch ambulation. The fact that spring-loaded crutches do not result in increased preferred ambulation speed, relative to the traditional crutches, should not be considered disadvantageous. Increased ambulation speed during crutch ambulation may decrease stability, as well as increase the reaction forces that are transmitted to the upper extremities during crutch ambulation.

We also considered the relative timing between initial foot contact and spring decompression during spring-loaded-crutch ambulation, because this timing may affect the spring’s ability to propel the patient forward. Initial foot contact occurred before spring decompression for 16 of the 20 subjects (an average of 46 ms before). It is not completely clear how this timing affects the spring’s ability to increase forward velocity for the patient. We speculate that because the foot usually contacts the ground before the spring decompresses, a torque is created about the foot–ground interface that may increase forward velocity for the patient. The forward, upward force that is applied to the axillary region by the crutch may produce a torque that rotates the patient forward and upward. Perhaps a posteriorly directed force applied to the axillary region by the crutch creates a torque that counters the aforementioned torque during another time of ambulation (eg, immediately after initial crutch–ground contact).

One potential limitation of the spring-loaded-crutch design we tested is that it comes with only 1 spring stiffness (12.95 kN/m). Considering this stiffness and the compressive preload that is applied to the spring (220 N), relatively small (less than ~45 kg) or large (greater than ~113 kg) patients may not benefit as much as average-size subjects. Smaller patients may not fully compress the spring, resulting in less stored elastic potential energy. This disadvantage may be minimized by using a lesser preload or more compliant spring. On the other hand, larger patients may fully compress the spring or “bottom out.” This “bottoming out” would also lessen stored elastic potential energy but could be avoided by using a stiffer spring. Addressing the challenge of variable body mass via the manipulation of spring stiffness or preload will also affect the crutch’s shock-absorption capabilities. Ideally, varying spring stiffnesses and preload magnitudes could be used depending on each patient’s mass. This concept was previously discussed in greater detail. None of the current subjects were smaller than 45 kg or larger than 113 kg, so the current results cannot elucidate this issue.

There are limitations related to this study. Only variables relating to forward progression of the center of mass were considered, because we believe these variables to be the most clinically important. Patients need forward motion to perform daily tasks. Mechanical energy transmitted from the spring-loaded crutch, however, likely affects other kinematic measures including segmental angular velocities, as well as vertical and mediolateral velocities. Other factors also limit the inferences that can be made from the current study. Only healthy subjects were tested, and
these subjects may not have used the crutches in the same way that habitual crutch users might. The selection of young healthy subjects, however, likely minimized between-subjects variability; because multiple pathologies necessitate crutch use and the mechanics of crutch ambulation are likely influenced by pathology, healthy subjects allow for the evaluation of crutch mechanics without the involved pathology acting as a confounding variable. Previous researchers have used healthy subjects to study spring-loaded-crutch ambulation for similar reasons.14

Conclusions

In summary, the tested spring-loaded crutch did store some elastic potential energy, as a result of a compressed spring located in the crutch post, during the crutch–ground contact phase of crutch ambulation. Some of this energy appears to have been converted to kinetic energy and transmitted to the subjects in a manner that facilitated forward motion; this was reflected in a peak instantaneous forward velocity immediately after spring decompression that was greater during spring-loaded-crutch ambulation than during traditional-crutch ambulation. Note, however, that this difference was relatively small and did not appear to affect preferred ambulation speed, which was not different between spring-loaded- and traditional-crutch ambulation. The forward velocity that is gained as a result of the decompressing spring may be lost when the subject compresses the spring during initial crutch–ground contact.

Acknowledgments

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References