Metabolic Energy Expenditure During Spring-Loaded Crutch Ambulation

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Context: Individuals using traditional axillary crutches to ambulate expend approximately twice as much energy as individuals who perform able-bodied gait. A relatively novel spring-loaded crutch now being marketed may reduce metabolic energy expenditure during crutch ambulation. This idea, however, had not yet been tested. Objective: To determine whether the novel spring-loaded crutch reduces oxygen consumption during crutch ambulation, relative to traditional-crutch ambulation. A secondary purpose was to evaluate the design for subject-perceived comfort and ease of use. Design: Within-subject. Setting: Indoor track. Participants: 10 able-bodied men and 10 able-bodied women. Interventions: The independent variable was crutch design. Each subject ambulated using 3 different crutch designs (traditional, spring-loaded, and modified spring-loaded), in a randomized order. Main Outcome Measures: The primary dependent variable was oxygen consumption. Secondary dependent variables were subject-perceived comfort and ease of use, as rated by the subjects using a 100-mm visual analog scale. Dependent variables were compared among the 3 crutch designs using a 1-way repeated-measures ANOVA (α = .05). Results: Oxygen consumption during spring-loaded-crutch ambulation (17.88 ± 2.13 mL · kg⁻¹ · min⁻¹) was 6.2% greater (P = .015; effect size [ES] = .50) than during traditional axillary-crutch ambulation (16.84 ± 2.08 mL · kg⁻¹ · min⁻¹). There was no statistically significant difference (P = .068; ES = -.45) for oxygen consumption between spring-loaded-crutch ambulation and ambulation using the modified crutch (17.03 ± 1.61 mL · kg⁻¹ · min⁻¹). Subjects perceived the spring-loaded crutch to be more comfortable (P < .001; ES = .56) than the traditional crutch. There was no difference (P = .159; ES = -.09) between the spring-loaded and traditional crutches for subject-perceived ease of use. Conclusions: Compared with traditional axillary crutches, the novel spring-loaded crutch may be more comfortable but does not appear to benefit subjects via reduced metabolic energy expenditure.

Keywords: rehabilitation, gait, oxygen consumption, sport medicine

Approximately 600,000 Americans use crutches to ambulate. Ambulation using traditional axillary crutches requires approximately twice as much metabolic energy as able-bodied gait. Despite this increased metabolic cost, patients benefit

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psychologically and physiologically when using crutches to move about rather than remaining immobile. A crutch design that facilitates patient mobility while decreasing metabolic costs, relative to traditional axillary-crutch ambulation, could potentially benefit crutch users.

Two different manufacturers (DJO Inc, Vista, CA, and Millennial Medical Inc, Logan, UT) are now marketing a relatively novel spring-loaded crutch. This new crutch design includes a spring that is located in the distal crutch post (Figure 1) and may facilitate decreased energy expenditure relative to traditional-crutch ambulation. During each cycle of crutch ambulation, the spring compresses, stores elastic potential energy, and then decompresses. During spring decompression, a portion of the stored elastic potential energy is converted to kinetic and gravitational potential energy. Theoretically, this additional mechanical energy may be transmitted to the patient, facilitate forward motion, and reduce metabolic energy expenditure during crutch ambulation. This idea is similar to spring-like tendons that stretch, store elastic potential energy, and facilitate energy conservation during human and animal locomotion. This idea of energy conservation during spring-loaded-crutch ambulation has been hypothesized but not objectively evaluated.

The primary purpose of this study was to determine whether the aforementioned spring-loaded-crutch design decreases metabolic energy expenditure during crutch ambulation relative to traditional axillary crutches. Because we expected that some mechanical energy would be transmitted from the spring-loaded crutch to the patient during ambulation, we hypothesized that spring-loaded-crutch ambulation would

![Figure 1](image-url) — The spring-loaded-crutch design tested in the current study.
require less oxygen consumption than traditional-crutch ambulation. To further evaluate the practical value of this relatively new spring-loaded-crutch design, we assessed the spring-loaded and traditional crutches for subject-perceived comfort and ease of use. We hypothesized that because of the springs in each crutch post, altered hand supports, and larger axillary-support regions, subjects would perceive the spring-loaded crutches to be more comfortable and easier to use than traditional axillary crutches.

**Methods**

Ten healthy women and ten healthy men (age 24 ± 4 y, height 1.74 ± 0.10 m, mass 73 ± 10 kg) gave written informed consent and participated in this study. Subjects wore shorts, a T-shirt, and athletic shoes during a single data-collection session. A within-subject design was used. Each subject ambulated using 3 different crutch designs: traditional, spring-loaded (Rebound Crutch, DJO Inc, Vista, CA), and modified spring-loaded. The modified spring-loaded design was identical to the spring-loaded design, except the spring in the crutch post was disabled. We tested the modified design to determine whether potential between-crutches differences were a result of the spring or other differences between the spring-loaded and traditional crutches (eg, crutch shape or altered hand supports). Crutch order was completely randomized, and subjects rested 15 minutes between sessions using each crutch design. For each crutch design, subjects were first allowed a 15-minute familiarization period. They then ambulated 300 m at a standardized speed (1 m/s) on a level surface over a period of 5 minutes (Figure 2). We carried a stopwatch alongside the subjects and counted each second out loud to ensure that they maintained the standardized ambulation speed; markers were placed every 5 m along the ambulation path, and subjects were instructed to pass a marker every 5 seconds. Maintaining the standardized speed appeared to be relatively easy for all subjects. Oxygen consumption was recorded every 5 seconds during the fifth minute using a ParvoMedics TrueMax 2400 metabolic cart (ParvoMedics, Sandy, UT). For each subject, oxygen consumption was averaged across the fifth minute for each crutch design.

After using each crutch design, subjects rated the design for comfort and ease of use. This was accomplished using 2 visual analog scales. Subjects answered the following 2 questions for each crutch design: How comfortable was this crutch while walking? How difficult was it to walk using this crutch? Subjects answered each question by placing a mark on a 100-mm line that ranged from not comfortable (on the far left) to very comfortable (on the far right) and not difficult (on the far left) to very difficult (on the far right). Sample means for the 3 dependent variables (oxygen consumption, subject-perceived comfort, and subject-perceived ease of use) were compared among the 3 crutch designs using a 1-way repeated-measures ANOVA (α = .05). If the ANOVA revealed differences among the 3 crutch types, post hoc comparisons were used to identify potential between-crutches differences. These post hoc comparisons were adjusted using Sidak’s method. In addition, the effect size (ES) was calculated for each comparison to better interpret any potential between-crutches differences.
Results

Means and standard deviations for oxygen consumption related to the 3 crutch designs are presented in Figure 3. A significant between-crutches difference was detected for oxygen consumption ($P = .007$). Post hoc analyses indicated that subjects consumed 6.2% more oxygen ($P = .015$; ES = .50) during spring-loaded-crutch ambulation (17.88 ± 2.13 mL · kg$^{-1}$ · min$^{-1}$) than during ambulation using traditional axillary crutches (16.84 ± 2.08 mL · kg$^{-1}$ · min$^{-1}$; Figure 1). There were no significant differences in oxygen consumption between the spring-loaded and modified crutches (17.03 ± 1.61 mL · kg$^{-1}$ · min$^{-1}$; $P = .068$; ES = .45) or between the traditional and modified crutches ($P = .901$; ES = −.11). In addition, there was no statistically significant difference ($P = .079$) for respiratory-exchange ratio among the spring-loaded (0.90 ± 0.06), traditional (0.89 ± 0.06), and modified (0.91 ± 0.05) crutches.

Means and standard deviations for subject-perceived levels of comfort and ease of use are shown in Figure 4. There were significant between-crutches differences for comfort ($P < .001$) and ease of use ($P < .001$). Regarding subject-perceived
comfort, post hoc comparisons showed that subjects perceived the traditional crutches to be less comfortable than the spring-loaded ($P < .001; \text{ES} = -.56$) and modified ($P < .001; \text{ES} = -.40$) crutches, but there was no difference between the spring-loaded and modified crutches ($P = .091; \text{ES} = .15$; Figure 4B). Regarding ease of use, the modified crutches were perceived to be less difficult to use than the traditional ($P = .001; \text{ES} = -.31$) and spring-loaded ($P = .001; \text{ES} = -.23$) crutches, but there was no difference between the traditional and spring-loaded crutches ($P = .159; \text{ES} = .09$; Figure 4A).

**Discussion**

The primary purpose of this study was to determine whether a relatively new spring-loaded-crutch design facilitates decreased metabolic energy expenditure during crutch ambulation relative to ambulation using traditional axillary crutches. We hypothesized that, because of mechanical energy that may be transmitted to the subjects from the spring-loaded crutch, less oxygen would be consumed during spring-loaded-crutch ambulation. The results contradicted our hypothesis and indicated that using the spring-loaded crutches increases oxygen consumption during crutch ambulation relative to traditional-crutch ambulation (Figure 3). In addition, a medium ES of .50 and relatively low $P$ value (.068) indicate that there may actually be a difference for energy expenditure between the modified and
Seeley et al. traditional-crutch designs. All these results indicate that spring-loaded-crutch and traditional-crutch ambulation are similar in that both require notably more oxygen than what is required during typical able-bodied walking.

The current data fit with previously reported data. To the best of our knowledge, only LeBlanc et al. have compared the metabolic costs of spring-loaded- and traditional axillary-crutch ambulation. They studied a sample of 5 disabled subjects and reported energy expenditure indices of .80 and .90 for traditional- and spring-loaded-crutch ambulation, respectively. Although no significant between-crutches difference was reported for the energy-expenditure index, the direction of the aforementioned difference between means is comparable to our results: The mean energy-expenditure index was greater, although not statistically significantly, for spring-loaded crutches than for traditional axillary crutches. Perhaps if a larger sample had been involved, these differences would have been statistically significant.

Figure 4 — Patient-perceived levels of (A) ease of use and (B) comfort, as rated on a 100-mm visual analog scale, for the 3 tested crutch designs. For ease of use, 0 mm indicated not difficult and 100 mm, very difficult. For perceived comfort, 0 mm indicated not comfortable and 100 mm, very comfortable. The traditional crutches were perceived to be less comfortable than the spring-loaded and modified crutches. *Statistical difference.
In addition, our data for metabolic energy expenditure during traditional-crutch ambulation at a speed of 1 m/s are comparable to previously reported values for traditional-crutch ambulation at similar speeds.\textsuperscript{2,3}

To speculate, 3 factors may have contributed to the increased metabolic costs that we observed during spring-loaded-crutch ambulation. First, the mass of the spring-loaded crutches we tested (4.40 kg) was greater than the mass of the traditional crutches (3.60 kg). Second, kinematic data for the spring-loaded crutches have indicated that the spring-loaded crutch is nearly vertical relative to the ground during spring decompression.\textsuperscript{7} This vertical orientation would limit the ability of the spring-loaded crutch to propel the subject forward yet facilitate upward motion of the subject (not completely dissimilar to a pogo stick). This upward motion results in increased gravitational potential energy for the subject during each gait cycle. This additional gravitational potential energy is subsequently converted to kinetic energy as gravity pulls the whole-body center of mass back toward the ground. As the center of mass lowers and heel strike occurs, muscle activity is likely required to absorb this additional kinetic energy during each gait cycle. Increased gravitational potential energy and the associated increased kinetic energy may increase the muscle force necessary to slow the falling center of mass during each gait cycle. This would likely increase the metabolic energy required during spring-loaded-crutch ambulation. Finally, some of the additional metabolic cost during spring-loaded-crutch ambulation may be related to the mechanical energy that is required to deform the spring during spring-loaded-crutch ambulation. Even if body weight is the primary force that causes spring deformation, the subject’s forward velocity is likely decreased during spring compression, and metabolic energy would be required later in the gait cycle to make up for this lost velocity.

A secondary purpose of the current study was to evaluate the spring-loaded-crutch design for patient-perceived comfort and ease of use. Our subjects reported that the spring-loaded crutches were more comfortable than the traditional and modified crutches (Figure 4B). This observation indicates that the spring and other differences between spring-loaded and traditional crutches (eg, unique overall shape of the crutch, different handgrip angle, and larger axillary-support region) contribute to the perceived difference in comfort. These results fit with previous anecdotes that indicated that spring-loaded crutches are more comfortable than traditional axillary crutches.\textsuperscript{14} Subjects did not report a statistically significant difference for ease of use between the spring-loaded and traditional crutches, but they did perceive the modified crutches as easier to use than the spring-loaded and traditional crutches (Figure 4A). This might indicate that the aforementioned unique shape of the spring-loaded crutch, more than the spring itself, contributes to its ease of use. These results are important to consider because perceived comfort and ease of use may be equally or more important to patients who require crutches to ambulate than reduced metabolic costs.

Because ambulation speed affects energy expenditure, we chose to control for speed by using an ambulation speed (1 m/s) that is easy to monitor and is in the midrange of speeds exhibited by crutch users.\textsuperscript{15} In addition, our selected speed has been shown to be most efficient for crutch users.\textsuperscript{15} The use of a standardized speed and the within-subject design of the current study add to our confidence in the observed differences—all subjects used each crutch design at the same speed, and the observed differences are likely related to crutch type rather than ambulation.
speed. Previous researchers who compared energy expenditure between traditional axillary and novel crutches also used a standardized ambulation speed. In addition, it was recently demonstrated that there is no statistically significant difference between a standardized ambulation speed of 0.97 m/s and preferred ambulation speed while using traditional axillary or spring-loaded-crutches. Alternatively, however, the standardized ambulation speed may limit the inferences that can be made from the current results—it is possible that if each subject had ambulated at a self-selected speed, rather than 1 m/s, some small differences in energy cost may have been detected.

Another limitation of this study is that only able-bodied subjects were tested, and these subjects were only allowed 15 minutes to become accustomed to the crutches. Because of this relatively short familiarization period, our subjects may not have used the crutches in a manner similar to that of habitual crutch users. The selection of young able-bodied subjects, however, likely minimized between-subjects variability. Because a wide variety of pathologies necessitate crutch use, and metabolic cost during crutch ambulation is likely influenced by pathology, able-bodied subjects allow for the evaluation of crutch mechanics without pathology acting as a confounding variable. Perhaps these same factors influenced the other numerous researchers who involved able-bodied subjects when asking similar research questions. Researchers have also involved able-bodied subjects in research related to muscle-activation patterns, whole-body kinematics, and kinetics that are involved during crutch ambulation.

In summary, the key finding of this study was that ambulation using the novel spring-loaded-crutch design requires more metabolic energy than traditional-crutch ambulation. Whatever additional mechanical energy that results from the decompressing spring is apparently negated. Although the spring-loaded design does not benefit patients via reduced metabolic energy expenditure, the spring-loaded crutches do appear to be more comfortable than traditional axillary crutches. There are numerous individuals who rely on axillary crutches to ambulate, and crutch ambulation requires significantly more metabolic energy than able-bodied walking, so an axillary-crutch design that minimizes metabolic cost would benefit many patients.

Acknowledgments

We want to acknowledge DJO Incorporated for providing the spring-loaded crutches that were tested during this study.

References