

# **A Mechanical Evaluation of a Novel Spring-loaded Crutch**

Original Article, Full Paper

Matthew K. Seeley<sup>1</sup>, PhD  
Iain Hunter<sup>1</sup>, PhD  
Tom Bateman<sup>1</sup>, BS  
Adam Roggia<sup>1</sup>, BS  
Brad J. Larson<sup>2</sup>, MD  
David O. Draper EdD<sup>1</sup>, ATC

<sup>1</sup> Department of Exercise Sciences  
Brigham Young University

<sup>2</sup> Alpine Orthopaedic Specialists

Corresponding Author  
Matthew K. Seeley  
Brigham Young University  
Department of Exercise Sciences  
116B RB  
Provo, UT 84602  
Phone: 801-422-4970  
Fax: 801-422-0555  
Email: matt\_seeley@byu.edu

Key Words:  
Crutches, Mechanical Energy, Rehabilitation, Spring

Total Word Count, Including Abstract: 2357

1 Abstract (Abstract Word Count = 247 Words)

2 A novel spring-loaded crutch design may provide additional kinetic energy to patients,  
3 however, this idea had been objectively evaluated. The purpose of this study was to evaluate the  
4 idea that the novel spring-loaded crutch design does provide additional kinetic energy to  
5 subjects, relative to traditional crutches. We hypothesized that subjects using the spring-loaded  
6 crutch design would exhibit more peak kinetic energy, in the forward direction, during the final  
7 stage of crutch-ground contact than subjects using traditional crutches. Crutch ambulation for  
8 twenty healthy subjects was observed. The independent variable was crutch type (spring-loaded  
9 and traditional). The primary dependent variable was peak kinetic energy for the center of mass  
10 in the forward direction during the final stage of crutch-ground contact. All subjects ambulated  
11 using spring-loaded and traditional crutches at a standardized speed ( $0.97 \text{ m/s} \pm 5\%$ ). Whole-  
12 body center of mass velocity in the forward direction was determined via video, and kinetic  
13 energy was calculated. Differences between crutch types for kinetic energy were evaluated using  
14 a paired  $t$ -test ( $\alpha = 0.05$ ). Peak kinetic energy in the forward direction was 9.6% greater ( $p =$   
15  $0.001$ ;  $t_{0.05,19} = -4.157$ ) for subjects using the spring-loaded crutch design. These results  
16 supported our hypothesis and demonstrated that the spring-loaded crutch design provides  
17 patients with additional kinetic energy, relative to traditional crutches. Based upon these data,  
18 one might expect that the spring-loaded crutch design decreases metabolic energy expenditure,  
19 however, a direct measure of metabolic cost during spring-loaded crutch ambulation is necessary  
20 to definitively clarify this issue.

21

22

23

## Introduction (Word Count = 460)

24  
25 Humans have used crutches to overcome gait impairments for thousands of years, and  
26 approximately 600,000 Americans use crutches each year [1]. Crutch design has evolved in that  
27 time [2], however, the typical traditional axillary crutch use is still problematic for two primary  
28 reasons: 1) increased upper extremity pathology [3-6], and 2) increased energy expenditure [7-  
29 10]. Repetitive high-magnitude forces are transmitted to the upper extremities during traditional-  
30 crutch ambulation and often lead to upper-extremity pathologies [3, 4]. Additionally, traditional-  
31 crutch ambulation requires approximately twice as much metabolic energy than healthy walking  
32 [7-10]. Despite these two challenges, individuals benefit psychologically and physiologically  
33 when using traditional crutches to move about, rather than remaining immobile [3].

34 Spring-loaded crutches were designed to minimize both of the aforementioned problems  
35 [11-14]. Spring-loaded crutches contain one or more springs in the crutch post and may decrease  
36 metabolic energy expenditure by storing and releasing mechanical energy during certain key  
37 times of crutch ambulation. The springs compress, storing strain energy during crutch-ground  
38 contact, and then decompress, converting the stored strain energy into kinetic and gravitational  
39 energy. In theory, if this kinetic energy is effectively transmitted to the center of mass of the  
40 patient, in the forward direction, metabolic energy expenditure might be reduced. This type of  
41 energy storage and release is similar to the manner in which humans and other mammals store  
42 strain energy in stretched tendons and then convert that stored energy into kinetic energy during  
43 walking and running [15, 16]. Some mechanical characteristics of spring-loaded crutch  
44 ambulation were previously described [12, 13, 15], however, a quantitative description of the  
45 strain energy being stored and then converted into kinetic energy during spring-loaded crutch  
46 ambulation has not yet been reported.

47 Two companies (Donjoy Incorporated, Vista, CA, USA and Millennial Medical, Logan,  
48 UT, USA) are currently marketing a nearly-identical spring-loaded crutch design (Figure 1).  
49 Both manufacturers purport that this crutch design returns captured strain energy to the patient  
50 and helps the patient move forward. Prior to this study, however, these purported mechanical  
51 benefits of this spring-loaded crutch design had not been quantified. The purpose of this study  
52 was to compare certain mechanical characteristics of spring-loaded and traditional-crutch  
53 ambulation. To accomplish this purpose, we: 1) quantified strain energy that is stored in the  
54 spring of the spring-loaded crutch during ambulation; 2) quantified peak kinetic energy for  
55 subjects immediately following decompression of the crutch spring during ambulation; and 3)  
56 compared this peak kinetic energy to peak kinetic energy at a comparable time during traditional-  
57 crutch ambulation. We hypothesized that peak kinetic energy for the center of mass in the  
58 forward direction would be greater during spring-loaded crutch ambulation than during  
59 traditional-crutch ambulation. We expected this difference in kinetic energy to result from strain  
60 energy that was stored by the crutch spring and then transmitted to patients.

#### 61 Methods (Word Count = 651)

62 Ten healthy males and ten healthy females (age =  $23 \pm 2$  years; height =  $1.73 \pm 0.10$  m;  
63 mass =  $69.2 \pm 13.7$  kg) provided informed consent and participated in this study. Male subjects  
64 wore footwear and spandex shorts, and female subjects wore footwear, spandex shorts, and a  
65 sports bra. A within-subjects design was used, so that all subjects used both crutch designs to  
66 ambulate. The specific spring loaded crutch design that was used during this study was the In  
67 Motion Pro model, manufactured by Millennial Medical Incorporated. Both crutch types were fit  
68 to each subject using accepted methods [17]. Crutch design order was randomized. To ensure  
69 that subjects were comfortable with both crutch designs, subjects ambulated 100 m with each

70 crutch design prior to data collection and then provided feedback to the examiners (no negative  
71 feedback was noted). Three-point crutch ambulation, with the dominant leg contacting the  
72 ground, was performed for all trials. Thirty-five reflective markers were applied to various  
73 anatomical landmarks using the VICON Plug-In Gait marker arrangement (Figure 2). This  
74 arrangement has been shown to accurately facilitate calculation of whole-body center of mass  
75 position [18]. Reflective markers were also attached to the crutches (Figure 2). For the spring-  
76 loaded crutch, reflective markers were applied distal and proximal to the spring, in order to  
77 quantify spring deformation.

78         Subjects performed three ambulation trials at a standardized average speed of 0.97 m/s  $\pm$   
79 5% [19]. This speed was used so that any differences in peak kinetic energy during crutch-  
80 ground contact between crutch types could not be attributed to differences in average speed. An  
81 opto-electronic timing device (Brower Timing Systems, Draper, UT, USA) was used to provide  
82 immediate feedback regarding average ambulation speed to subjects, assisting them in  
83 maintaining the standardized speed. Video data were collected (60 Hz; VICON, Centennial, CO,  
84 USA) for all trials. Three-dimensional coordinates for each reflective marker were tracked and  
85 digitally filtered using the Woltring filter in VICON Nexus 1.3 software.

86         Strain energy, stored and released by the spring-loaded crutch during crutch-ground  
87 contact, was calculated using the standard equation: Strain Energy (J) =  $\frac{1}{2} \cdot k \cdot x^2$ ;  $k$  indicates  
88 spring stiffness (12.95 KN/m), as reported by the manufacturer, and  $x$  indicates the magnitude of  
89 spring deformation. This deformation was calculated by quantifying the change in distance  
90 between the two spring-loaded crutch markers that were just proximal and distal to the spring  
91 during two different phases of ambulation: 1) prior to crutch-ground contact, and 2) maximal

92 spring deformation. Strain energy was averaged across the three trials for each crutch design, for  
93 each subject.

94 Kinetic energy for the subject's center of mass, in the forward direction, was calculated  
95 using the aforementioned coordinate data. Center of mass velocity was derived from the  
96 coordinate data and kinetic energy was determined using the standard equation: Kinetic Energy  
97 ( $J$ ) =  $\frac{1}{2} \cdot m \cdot v^2$ ;  $m$  indicates subject mass, and  $v$  indicates center of mass velocity in the forward  
98 direction. Next, peak kinetic energy during crutch-ground contact was identified. For all of the  
99 spring-loaded crutch trials, this peak consistently occurred immediately after spring  
100 decompression, just prior to the end of crutch-ground contact. This peak also occurred at a  
101 consistent time during the traditional crutch trials, just before the end of crutch-ground contact.  
102 Peak kinetic energy was averaged across the three trials for each crutch design, for each subject.

103 A paired  $t$ -test was used to compare means for peak kinetic energy for the center of  
104 mass in the forward direction between the two crutch designs. A paired  $t$ -test was also used to  
105 compare mean ambulation speeds between the two crutch designs, to ensure that ambulation  
106 speed was properly controlled for. Alpha was set at 0.05 for both comparisons. We assumed  
107 strain energy, stored in the traditional crutch, to be negligible and did not compare strain energy  
108 between crutch types. Means and standard deviations were used to describe strain energy that  
109 was stored by the spring-loaded crutch during ambulation.

#### 110 Results (Word Count = 106)

111 Table 1 shows the means and standard deviations for both crutch designs for: 1) peak  
112 velocity and kinetic energy for the center of mass in the forward direction, and 2) average  
113 ambulation speed. Peak velocity was 5% greater ( $p < 0.001$ ;  $t_{0.05,19} = -4.598$ ) and peak kinetic  
114 energy was 9.6% greater ( $p = 0.001$ ;  $t_{0.05,19} = -4.157$ ) during spring-loaded crutch ambulation,

115 relative to traditional crutch ambulation. Mean ambulation speeds did not significantly differ ( $p =$   
116  $0.396$ ;  $t_{0.05,19} = 0.868$ ) between the spring-loaded and traditional crutch trials. Table 1 also shows  
117 the average magnitude of strain energy that was stored by the spring-loaded crutch during crutch-  
118 ground contact.

#### 119 Disucssion (Word Count = 862)

120 The purpose of this study was to compare certain mechanical characteristics of spring-  
121 loaded and traditional crutch ambulation. We tested a specific spring-loaded crutch design that is  
122 presently being marketed. Manufacturers of this specific crutch design purport that mechanical  
123 energy is returned to the patient, helping the patient move forward. The spring, located within the  
124 crutch post, compresses during crutch-ground contact and stores strain energy. The spring then  
125 decompresses near the end of crutch-ground contact and, theoretically, the stored strain energy is  
126 converted into kinetic and gravitational energy. Some of this kinetic energy may be transferred to  
127 the patient in the forward direction, benefitting the patient. This idea of energy transfer, however,  
128 had not been objectively evaluated. We expected that subjects would exhibit greater peak kinetic  
129 energy during spring-loaded crutch ambulation, relative to traditional crutch ambulation. The  
130 data confirmed this expectation, as peak kinetic energy in the forward direction was 9.6% greater  
131 for subjects during spring-loaded crutch ambulation. We believe this difference in peak kinetic  
132 energy is related to additional energy that is stored within the spring of the spring-loaded crutch  
133 and, speculating, may decrease energy expenditure during spring-loaded crutch ambulation.

134 This study adds to the present knowledge regarding crutch ambulation. Our data, in  
135 combination with previous research, indicate that spring-loaded crutches may benefit patients by  
136 minimizing two major challenges for patients who use traditional crutches during ambulation: 1)  
137 upper-extremity pathology due to repetitive forces that are transmitted to hands and underarms,

138 and 2) increased metabolic expenditure. Previous research has indicated that spring-loaded  
139 crutch use optimizes various characteristics of the ground reaction force (peak force, rate of force  
140 application, and impulse due to ground reaction force) and decreases the risk of chronic upper-  
141 extremity injury due to repetitive forces [13-15]. The present data indicate that spring-loaded  
142 crutches may also decrease energy expenditure, as a result of additional mechanical energy that  
143 comes from spring decompression during the latter part of crutch-ground contact.

144 We observed an average of five additional Joules of kinetic energy for the center of mass  
145 in the forward direction during spring-loaded crutch ambulation, relative to traditional crutch  
146 ambulation. However, only 2.5 Joules of additional energy were stored and released by the  
147 spring-loaded crutches, indicating that the springs were not the only contributor to additional  
148 kinetic energy in our subjects during spring-loaded crutch ambulation. Perhaps, the unique shape  
149 of the spring-loaded crutches also contributed additional kinetic energy during ambulation. The  
150 unique shape of the spring-loaded crutch may have caused an increase in upper-extremity  
151 kinetics (e.g., an increased shoulder extension moment) or electromyography (e.g., increased  
152 latissimus dorsi or posterior deltoid activity) near the end of crutch-ground contact. These  
153 hypothetical increases in upper-extremity joint kinetics or electromyography may also have  
154 contributed, in combination with the additional strain energy from the spring, to increase kinetic  
155 energy. A comparison of upper-extremity joint kinetics, joint kinematics, and electromyography  
156 between spring-loaded and traditional crutch ambulation may clarify the source of this additional  
157 kinetic energy.

158 One limitation of the spring-loaded crutch design that was tested is the overly compliant  
159 nature of the spring. The stiffness of the spring is 12.95 kN/m (74 lb/in), as reported by the  
160 manufacturer, which is considerably less than what was previously recommended for spring-

161 loaded crutches (22 kN/m; [3]). A consequence of this relatively compliant spring is that many  
162 adult subjects will not store as much as strain energy as they would if they used a crutch with a  
163 stiffer spring. If each crutch, within a pair of crutches, contains one spring of the aforementioned  
164 stiffness, each crutch will “bottom out” for any subject who weighs approximately 150 lbs or  
165 more. This “bottoming out” would not occur if a stiffer spring was used. Although the spring-  
166 loaded crutch did appear to store and transmit energy to the subjects, more energy would have  
167 likely been stored and transmitted if the spring was stiffer. A stiffer spring, however, will lead to  
168 reduced shock absorption, which must be considered when selecting spring stiffness.

169         This study is important as it is the first to measure strain and kinetic energy during  
170 spring-loaded crutch ambulation. Energy expenditure, however, was not directly measured. A  
171 direct measure of oxygen consumption during spring-loaded crutch ambulation would better  
172 clarify the role of a spring in reducing energy expenditure during crutch ambulation. Previous  
173 researchers reported that energy expenditure during spring-loaded crutch and traditional crutch  
174 ambulation was not significantly different [11]. One limitation to this study, however, was a  
175 small sample size of only six subjects. A comparable study including a larger sample and  
176 crutches that are presently commercially available may clarify the issue of energy expenditure  
177 during spring-loaded crutch ambulation.

178         In summary, spring-loaded crutches store strain energy as the spring in the crutch post  
179 compresses during the crutch-ground contact phase of ambulation. Some of this stored strain  
180 energy appears to be transmitted to the patient in the form of kinetic energy in the forward  
181 direction. This conversion of strain energy to additional kinetic energy may decrease energy  
182 expenditure during crutch ambulation, and is not dissimilar to humans and other mammals that  
183 benefit from strain energy that is stored in tendons during certain phases of gait. Although

184 subjects exhibited additional kinetic energy during the crutch-contact phase of crutch  
185 ambulation, a decrease in metabolic energy expenditure should not be assumed. A direct measure  
186 of oxygen consumption during spring-loaded and traditional crutch ambulation would  
187 definitively clarify this issue.

188

189

190

191

192

193

194

195

196

197

198

199

200

201

202

203

204

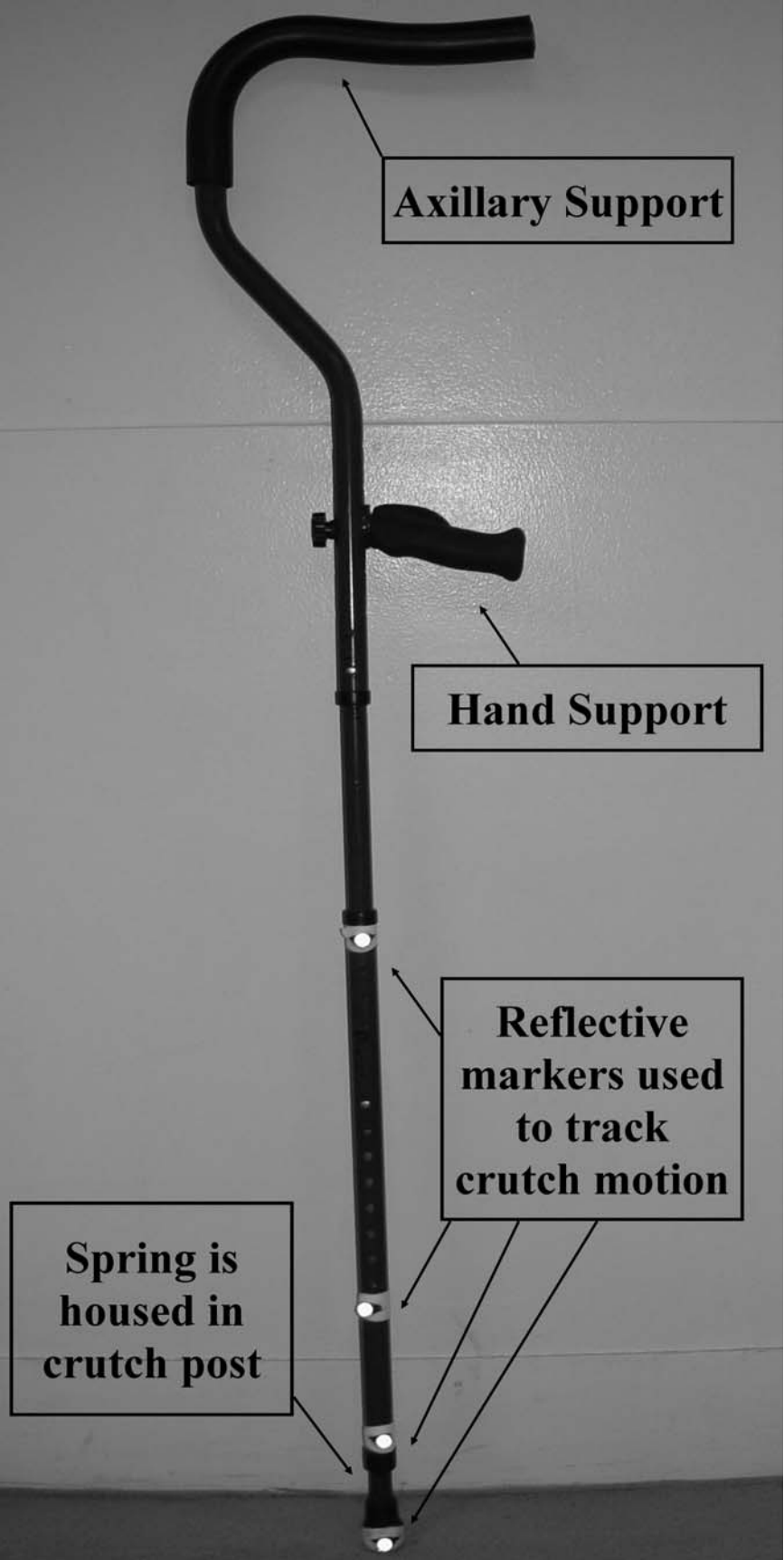
205

206

- 208 1. Russell J, Hendershot G, LeClere F, Howie L, Adler M. Trends and Differential Use of  
209 Assistive Technology Devices. *Vital and Health Statistics of the Centers for Disease*  
210 *Control and Prevention* 1994; 292: 1-10.
- 211 2. Bick EM. The classic source book of orthopaedics: primitive man and ancient practice.  
212 *Clin Orthop Relat R* 1979; 139: 2-16.
- 213 3. Shortell D, Kucer J, Neeley W, LeBlanc M. The design of a compliant composite crutch.  
214 *J Rehabil Res Dev* 2001; 38(1): 23-32.
- 215 4. Opila KA, Nicol AC, Paul JP. Upper limb loadings of gait with crutches. *J Biomech Eng*  
216 1987; 109(4): 285-290.
- 217 5. Waring W, Werner R. Clinical management of carpal tunnel syndrome in patients with  
218 long-term sequelae of poliomyelitis. *J Hand Surg-A* 1989; 14: 865-869.
- 219 6. Deathe A, Hayes K, Winter D. The biomechanics of canes, crutches, and walkers. *Crit*  
220 *Rev Phys Rehabil Med* 1993; 5(1): 1-15.
- 221 7. Waters RL, Campbell J, Perry J. Energy cost of three-point crutch ambulation in fracture  
222 patients. *J Orthop Trauma* 1987; 1(2): 170-173.
- 223 8. McBeath AA, Bahrke M, Balke B. Efficiency of assisted ambulation determined by  
224 oxygen consumption measurement. *J Bone Joint Surg AM* 1974; 56(5): 994-1000.
- 225 9. Roberts P, Carnes S. The orthopaedic scooter. An energy-saving aid for assisted  
226 ambulation. *J Bone Joint Surg BR* 1990; 72(4): 620-621.
- 227 10. Fisher S, Patterson R. Energy Cost of Ambulation with Crutches. *Arch Phys Med Rehab*  
228 1981; 62: 250-256.
- 229 11. LeBlanc M, Lawrence L, Nauenberg T. A quantitative comparison of four experimental  
230 axillary crutches. *J Prosthet Orthot* 1993; 5(1): 20-28.
- 231 12. Lewin P. An adjustable spring crutch. *J Bone Joint Surg* 1928; 10: 819-821.
- 232 13. Parziale J, Daniels J. The mechanical performance of ambulation using spring-loaded  
233 axillary crutches: a preliminary report. *A J Phys Med Rehab* 1989; 68(4): 193-195.
- 234 14. Shoup T. Design and testing of a child's crutch with conservative energy storage. *J Mech*  
235 *Design* 1980; 102: 672-676.
- 236 15. Segura A, Piazza S. Mechanics of ambulation with standard and spring-loaded crutches.  
237 *Arch Phys Med Rehab* 2007; 88: 1159-1163.
- 238 16. Alexander R. Walking and running. *Am Sci* 1984; 72(4): 348-354.
- 239 17. Prentice WE. *Arnheim's Principles of Athletic Training* 2003; McGraw-Hill Higher  
240 Education: New York, New York, USA.
- 241 18. Gutierrez-Farewik EM, Bartoneck A, Saraste H. Comparison and evaluation of two  
242 commone methods to measure center of mass displacement in three dimensions during  
243 gait. *Hum Movement Sci* 2006; 25: 238-256.
- 244 19. Thys H, Willems P, Saels P. Energy cost, mechanical work and muscular efficiency in  
245 swing-through gait with elbow crutches. *J Biomech* 1996; 29(11): 1473-1482.

|                          | Millennial Crutches | Traditional Crutches |
|--------------------------|---------------------|----------------------|
| Peak Velocity (m/s)*     | $1.29 \pm 0.08$     | $1.23 \pm 0.10$      |
| Peak Kinetic Energy (J)* | $57.3 \pm 12.0$     | $52.3 \pm 11.6$      |
| Strain Energy (J)        | $2.50 \pm 1.96$     | Negligible           |
| Ambulation Speed (m/s)   | $0.96 \pm 0.04$     | $0.97 \pm 0.02$      |

248 Table 1. Means and standard deviations describing the variables of primary interest for both  
249 crutch types. Peak velocity, peak kinetic energy, and strain energy were all considered during  
250 crutch-ground contact. Ambulation speed was the speed that the subject ambulated during the  
251 entire trial. These data support our hypotheses and indicate that the spring-loaded crutch provides  
252 additional kinetic energy to the subject in the forward direction, relative to traditional crutches.  
253 Asterisks indicate variables that were shown to be significantly different.  
254





259 Figure 1. The spring-loaded crutch that was tested in the present study. One spring is housed  
260 inside of the crutch post, as indicated. Reflective markers were attached to each crutch so that  
261 crutch motion could be described via high-speed videography. Markers were attached  
262 immediately distal and proximal to the spring so that spring compression could be quantified.

263  
264 Figure 2. A depiction of the reflective marker arrangement that was used in the present study.  
265 Thirty five marker were attached to various anatomical landmarks. Markers were also attached to  
266 the left and right crutches for both crutch types.