

ORIGINAL ARTICLE

Decreased Energy Cost and Improved Gait Pattern Using a New Orthosis in Persons With Long-Term Stroke

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ABSTRACT. Thijssen DH, Paulus R, van Uden CJ, Kooloos JG, Hopman MT. Decreased energy cost and improved gait pattern using a new orthosis in persons with long-term stroke. *Arch Phys Med Rehabil* 2007;88:181-6.

Objective: To measure energy cost and gait analysis in persons with stroke with and without a newly developed orthosis.

Design: Immediate and long-term (3wk) intervention (before-after trial).

Setting: University medical center.

Participants: Volunteer sample of 27 persons with long-term (range, 0.6–19y) hemiparetic stroke.

Intervention: Three-week familiarization to the new walking aid.

Main Outcome Measures: Energy cost (per distance walked), preferred walking speed (PWS), and step length. Energy cost was examined in all subjects while walking on a treadmill at 3 different velocities (PWS, PWS+30%, PWS–30%) during 3 different situations (without orthosis, with orthosis, after 3-wk orthosis familiarization). Spatiotemporal aspects of the gait pattern were examined using a 6-m instrumented walkway system.

Results: Using the orthosis immediately decreased energy cost in persons with stroke during walking at the PWS ($P<.001$) and significantly increased walking speed ($P<.005$) and step length ($P<.001$). After 3 weeks of familiarization to the orthosis, energy cost at the PWS and at PWS+30% showed further improvement in energy cost ($P<.05$).

Conclusions: The newly developed orthosis immediately decreases energy cost and improves walking speed and step length in persons with long-term stroke. After only 3 weeks of orthosis familiarization, energy cost shows additional improvement.

Key Words: Energy metabolism; Gait; Orthotic devices; Rehabilitation; Stroke.

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STROKE IS A MAJOR CAUSE of death and disability, leading to about 5 million people who die each year from stroke worldwide, while yearly 10 million people survive a

stroke.¹ These stroke survivors are often left with persistent neurologic deficits² that affect functional abilities, of which impaired gait is a central feature. Gait performance in persons with stroke is typically characterized by the spatiotemporal asymmetry between both sides, decreased walking speed, and problems with trunk-limb, interlimb, and intralimb coordination.³⁻⁶ These characteristics may eventually lead to a higher energy cost during walking in persons with stroke. The lower walking speed with higher energy costs predisposes stroke survivors to a sedentary life, which limits activities of daily living and impairs cardiovascular function.⁷ Improvement of the impaired gait pattern is therefore important in rehabilitation.

Gait training is a central goal of early rehabilitation.³ In the chronic phase, however, persons with stroke demonstrate less benefit from a given amount of gait training compared with the early phase.⁸ An ankle-foot orthosis (AFO) can be applied to partially correct the gait pattern,³ possibly decrease energy cost,^{3,9} and increase walking speed^{10,11} in persons with long-term stroke. However, these results are not universal¹² and seem to depend on the composition of the orthosis.¹¹ In addition, a shortcoming of the AFO is its effect at only 1 joint, while commonly the whole limb is affected by stroke.

In light of these limitations, a new orthosis^a has been developed (fig 1). This orthosis is intended to correct the gait pattern through the aid of elastic straps that guide the major joints of the affected limb, that is, hip, knee, and ankle. Therefore, the aim of this study was to examine the effect of this new orthosis on the energy cost and gait pattern in a heterogeneous group of long-term hemiparetic stroke survivors. We extended our knowledge about the potential effect of this orthosis, by measuring the persons with stroke after a 3-week orthosis familiarization period. We hypothesize that this orthosis will decrease energy cost and increase walking speed in persons with long-term stroke, after 3 weeks of familiarization.

METHODS

Participants

Twenty-seven chronic hemiparetic persons with stroke (time since stroke, 7–228mo) participated in the study. We selected these subjects from a larger population that responded to an advertisement in a newspaper. The persons with stroke were included in the study if they were able to walk 5 minutes or more, their time since stroke was 6 months or more, and they were free of overt neurologic (other than stroke) and/or orthopedic pathology that may influence the gait pattern. The Functional Ambulation Category (FAC) was used to provide a gross classification of the walking handicap¹³ (table 1). Prior to testing, all subjects gave their written informed consent. The research has been carried out in accordance with the Declaration of Helsinki and the medical ethics committee of the Radboud University Nijmegen Medical Centre approved the study.

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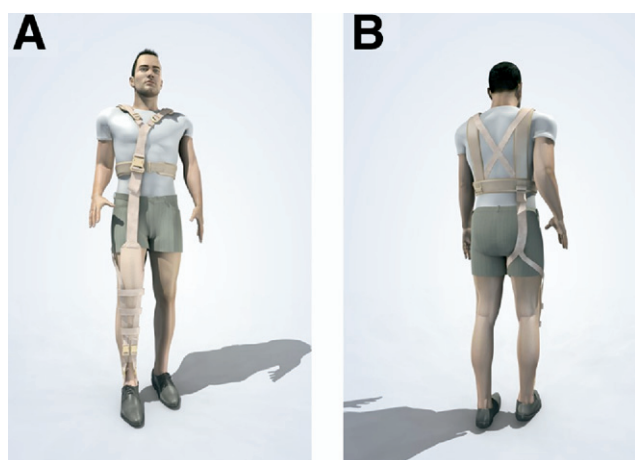


Fig 1. (A) The front and (B) back of the orthosis^a as used in this study.

Design

We measured the spatiotemporal aspects of the gait pattern on a walking system in a situation with and without the orthosis (fig 2). Energy cost was examined with and without the orthosis at 3 different walking speeds on a motor-driven treadmill (preferred walking speed [PWS] and 30% above [PWS+30%] and below [PWS-30%] this predetermined walking speed). To prevent influence of fatigue during the testing procedure, the sequence of the experiments (with and without the orthosis) was randomized. The procedure was repeated after 3 weeks of familiarization. This period was required for the participants to get used to walking with the orthosis.

Protocol

After completing the health questionnaires, subjects were randomized to determine whether the first procedure was performed with or without the orthosis (alternately based on entrance). We hypothesized that the working mechanism of the orthosis is based on the tension of the elastic straps. An experienced researcher applied the amount of tension on the straps. A simple functional test was used to examine whether sufficient tension was applied. The foot of the affected leg was placed 10cm behind the nonaffected foot (measured from the

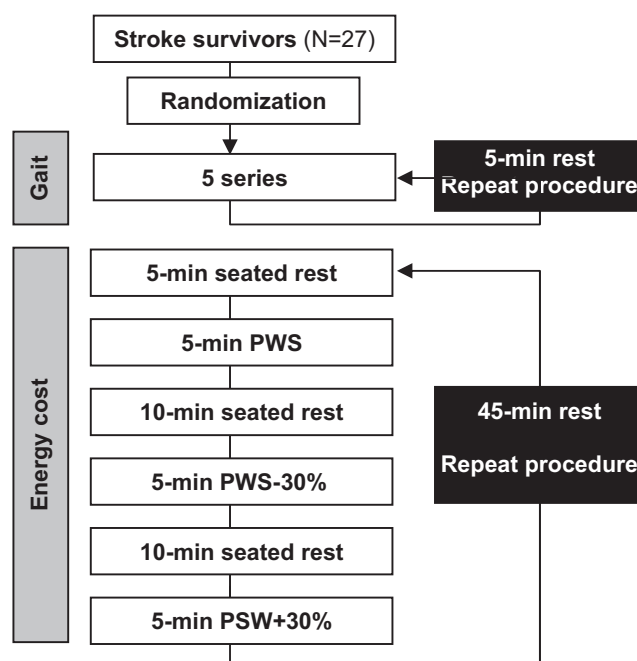


Fig 2. Experimental protocol. Before the experiment, randomization determined the order of the protocol (first trial with or without orthosis). First, the spatiotemporal aspects of the gait were examined. Subsequently, energy cost was determined at: (1) the preferred walking speed (PWS), (2) 30% below the PWS (PWS-30), and (3) 30% above the PWS (PWS+30).

heel of the unaffected leg to the toes of the affected leg). Subsequently, when body weight was shifted toward the nonaffected side, the affected leg should automatically swing forward. The procedure started with assessment of the spatiotemporal aspects of the gait pattern using a specially developed walking mat with integrated sensitive sensors. This mat was positioned to allow the subjects to begin walking 2m before the mat and to continue walking 2m past the end of the mat without slowing. Each subject was instructed to walk at a self-selected preferred walking speed. Data were collected for 5 consecutive trials.¹⁴ A researcher accompanied the persons with stroke (without verbal or physical assistance) for safety reasons. After completing the fifth trial, the subjects had a 5-minute seated rest before the procedure was repeated.¹⁴

The procedure was continued by assessment of the energy cost during walking. First, the PWS with and without the orthosis was determined on the motor-driven treadmill, while subjects were blinded for the walking speed. Subsequently, we instrumented the subjects to examine energy cost during walking. The experimental procedure started with a 5-minute seated rest, followed by a 5-minute period at the PWS^{3,9} (see fig 2). Next, the subjects had a 10-minute seated rest before the next trial started, which consisted of a 5-minute period at 30% below the PWS. The third trial (30% above the PWS) started after 10-minute seated rest. Due to safety reasons, all persons with stroke kept contact with the handlebar in front of them during walking, but did not use the handlebar for body weight support. In addition, subjects were connected to a safety brake that would be activated when the subjects could not maintain their walking speed. After 45 minutes of seated rest, this procedure was repeated.

Table 1: Subject Characteristics for the Persons With Stroke, Subdivided Based on the FAC

Characteristics	Overall (N=27)	FAC 3 (n=4)	FAC 4 (n=10)	FAC 5 (n=13)
Men/women	15/12	2/2	4/6	9/4
Age (y)	60±13	61±19	60±9	59±12
Weight (kg)	80±13	81±8	79±15	81±13
Height (cm)	172±9	173±5	168±10	174±7
Left side affected	15	2	7	6
Time since stroke (y)	4.9±4.8	2.8±2.3	4.9±5.9	5.5±4.2
Use of AFO	18	4	6	8
Use of cane/stick during walking	23	4	10	9
Orthopedic footwear	14	4	6	4
Randomization (start with orthosis)	13	2	4	7

NOTE. Values are mean ± standard deviation (SD).

Measurements

Energy cost. To examine energy cost, subjects walked on a motor-driven 1.2×3.1m long treadmill,^b while oxygen uptake was measured continuously using a gas analyzer.^c A face mask was placed over the mouth and nose, which allows normal breathing. Inspired and expired air goes into a turbine flowmeter for continuous registration of the inspired and expired volumes. In addition, a fast-response paramagnetic and infrared analyzer measured end-tidal partial pressures of oxygen and carbon dioxide, respectively.¹⁵ Oxygen uptake was monitored during the whole procedure, and averaged over 30-second intervals. This technique is demonstrated to be valid and has an excellent reproducibility to examine oxygen uptake.¹⁶

Gait pattern. We examined spatiotemporal parameters of the gait pattern using a walkway system.^d The walkway system is a 6-m long carpet with an active sensor area of 488×61cm. The active area has a spatial resolution of 1.27cm and a sampling frequency between 32.2 and 38.4Hz.¹⁴ In the present study, we evaluated walking speed (in m/s), cadence (in steps/min), step length (in centimeters), swing phase (in percent), and stance phase (in percent) of the affected and nonaffected side. These spatiotemporal gait parameters were demonstrated to have a good to excellent test-retest reliability.¹⁴

Data Analysis

Energy cost. We calculated energy cost at a given walking speed as a 1-minute plateau in oxygen uptake during the last minute of the interval.¹⁷ The energy cost per distance walked (in mL O₂/m) was calculated as oxygen uptake (during the last minute) divided by the distance walked in the last minute.

Gait pattern. Footsteps that did not fall entirely on the walkway were deleted. Mean values for each gait parameter were calculated using the first 10 complete steps derived from the 5 trials.¹⁴

Statistical Analysis

We performed statistical analyses using SPSS.^e According to the Kolmogorov-Smirnoff test for normality, all parameters

Table 2: The Direct Effect of the Orthosis on Walking Speed, Oxygen Cost, and Spatiotemporal Aspects of the Gait Pattern in Persons With Long-Term Hemiparetic Stroke

Variables	Day 1 (N=27)	
	Baseline	Orthosis
Walking speed (m/min)	23.7±12.7	26.0±14.0*
Oxygen cost		
PWS (mL O ₂ /m)	46±25	42±21*
PWS-30% (mL O ₂ /m)	54±28	53±26
PWS+30% (mL O ₂ /m)	41±21	40±20
Spatiotemporal aspects		
Cadence (steps/min)	74±19	77±17
Step length (A side), cm	41±13	44±13*
Step length (NA side), cm	37±16	40±15*
Swing phase (A side), %	32±8	35±6*
Swing phase (NA side), %	23±9	24±7*
Stance phase (A side), %	68±8	65±6*
Stance phase (NA side), %	77±9	76±7*
Double support (A side), %	45±15	41±12*
Double support (NA side), %	45±15	51±12*

NOTE. Values are mean ± SD. Oxygen cost is determined at the preferred walking speed and 30% above and below this walking speed. Spatiotemporal aspects were examined in the affected (A) and nonaffected (NA) side.

*P<.05 vs baseline (day 1).

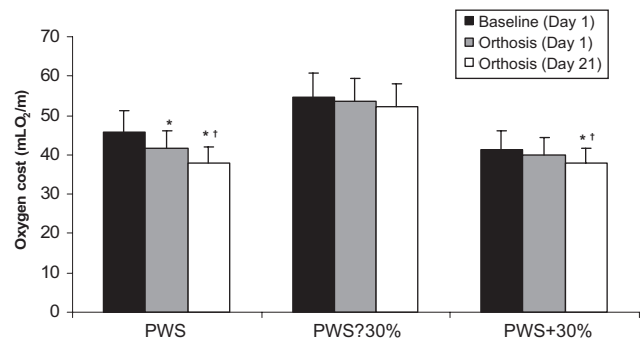


Fig 3. Oxygen cost at the preferred walking speed and 30% below and above the preferred walking speed in persons with long-term hemiparetic stroke (n=19). Each subject performed these walking speeds without the orthosis (baseline [day 1]) and with the orthosis on day 1 (orthosis [day 1]) and after 3 weeks familiarization (orthosis [day 21]). Values are mean ± standard error of the mean (SEM). *P<.05 vs baseline (day 1); **P<.05 vs orthosis (day 1).

were normally distributed. To examine the direct effect of the orthosis, a Student paired *t* test was used to examine the direct (baseline vs orthosis day 1) effect of the orthosis for all parameters and after 3 weeks of familiarization (baseline day 1 vs orthosis day 21). Goodman-Kruskal γ (for an ordinal and an interval or ratio variable) and Pearson correlation (for interval or ratio variables) were used to examine relations between parameters. Data are presented as mean ± standard deviation (SD). The level of statistical significance was set at α less than or equal to .05.

RESULTS

Direct Effects

Energy cost. On the treadmill, the orthosis significantly increased the PWS (table 2). The orthosis significantly decreased energy cost at the PWS, while no change in energy cost was found when the subject walked 30% lower or higher than the PWS (see table 2).

Gait pattern. Use of the orthosis increased step length, and swing phase on the affected and nonaffected side (see table 2). A significant reduction of the double-support and stance phase was present when the orthosis was used (see table 2). Cadence did not change (see table 2).

Three-Week Familiarization

Eight stroke survivors did not complete the familiarization period (hospitalization [n=2], burn wounds [n=1], time management [n=1], not able to independently use the orthosis [n=4]). During familiarization, persons with stroke (n=19) used the orthosis 33±3h/wk and walked 9±1h/wk.

Energy cost. After familiarization, the PWS did not increase any further (fig 3). Energy cost at the PWS, however, showed an additional decrease after 3 weeks of familiarization. In addition, a significantly lower energy cost was also present at the PWS+30%. No changes in energy cost were found at the PWS-30% (see fig 3).

Gait pattern. Step length (affected side, P=.09; nonaffected side, P=.10) and swing phase (affected side, P=.10) tended to increase, while the stance phase (affected side, P=.10) tended to decrease. The other parameters showed a significant further change after 3 weeks of familiarization (table 3).

Table 3: The Direct and Long-Term (3-week familiarization) Effect of the Orthosis on Spatiotemporal Aspects of the Gait Pattern in Persons With Long-Term Hemiparetic Stroke on the Affected and Nonaffected Side

Aspects	Day 1 (n=19)		Day 21 (n=19)
	Baseline	Orthosis	Orthosis
Walking speed (m/min)	24.7±13.7	27.6±14.3*	28.7±13.8*
Cadence (steps/min)	75±19	75±17	77±17
Step length (A side), cm	41±14	44±14*	47±12*
Step length (NA side), cm	39±17	42±16*	44±14*
Swing phase (A side), %	31±8	34±6*	35±5*
Swing phase (NA side), %	23±9	24±8*	26±6*†
Stance phase (A side), %	69±8	66±6*	65±5*
Stance phase (NA side), %	77±9	76±8*	74±6*†
Double support (A side), %	45±15	42±12*	39±9*†
Double support (NA side), %	47±16	42±12*	39±10*†

NOTE. Values are mean ± SD.

* $P < .05$ vs baseline (day 1).

† $P < .05$ vs orthosis (day 1).

Correlations

A significant inverse correlation was demonstrated between the FAC score and improvement in energy cost when the subject used the orthosis on day 1 ($r = .37$, $P = .02$) and after 3 weeks of familiarization (fig 4). In addition, the preferred walking speed correlated inversely with a change in oxygen uptake with the use of the orthosis on day 1 ($r = -.46$, $P = .016$) and after 3 weeks ($r = -.70$, $P = .001$). The relative increase in walking speed with the orthosis correlated with the decrease in oxygen uptake during walking on day 1 ($r = -.47$, $P = .01$) and after 3 weeks ($r = -.61$, $P = .005$).

DISCUSSION

In the present study we examined the effect of a new orthosis on energy cost and gait pattern in long-term hemiparetic stroke survivors. We showed that the use of the new orthosis resulted in an immediate increase in preferred walking speed and step length and a decrease in energy cost during walking. Three weeks of orthosis familiarization further decreased oxygen cost during walking. Thus, our results show marked beneficial ambulatory effects of this new orthosis in a heterogeneous group of chronic hemiparetic stroke survivors.

Direct Effect

Immediately when first using the orthosis, persons with stroke showed a significantly lower energy cost of 10% at the self-preferred walking speed with the orthosis. This improvement is comparable with previous studies examining the effect of an AFO.^{3,9} An important difference is that these studies examined persons with stroke after at least 4 months of rehabilitation using the AFO. To the best of our knowledge, no studies have examined the immediate effects of an AFO in persons with stroke.

Gait analyses demonstrated that stroke survivors in our study had a larger step length with orthosis, while the cadence was unchanged. Consequently, persons with stroke demonstrated a higher walking speed. The magnitude of the immediate increase in walking speed using the orthosis is consistent with the improvement in speed reported after long-term habituation to the AFO,^{3,9} although others report no change in walking speed with the AFO.¹¹ In addition, our results also demonstrate a longer swing phase and shorter stance phase of the affected and

nonaffected side with the use of the orthosis. Because the increase in duration of the swing phase on the affected side is similar to the increase on the nonaffected side, using the orthosis does not lead to a more symmetrical gait pattern. Nevertheless, the orthosis leads to a lower energy cost during walking.

When subjects were required to walk at a nonpreferred speed (+30% or -30%), the benefit of the orthosis to decrease oxygen cost that was present at the preferred walking speed disappeared. In physiologic and abnormal gait, the self-selected preferred walking speed is tightly regulated to minimize oxygen cost and walk efficiently.¹⁸ Forcing subjects to walk at a different speed will lead to a different gait pattern that diminishes the benefits in energy cost. This suggests that, at least in the initial phase, the orthosis only provides benefit at the self-selected walking speed.

Three-Week Familiarization

In addition to the immediate effect of the orthosis, 3 weeks of familiarization to the orthosis further lowered the energy cost at the preferred walking speed (up to 18%). Also, energy cost at the PWS+30% was decreased. This decrease in oxygen cost after 3 weeks familiarization is comparable with a previous study that examined the effects of an AFO after 6 months rehabilitation.³ Based on the short period of familiarization and the lack of training or rehabilitation in the present study, one may hypothesize that even larger improvements in energy cost and gait pattern could be achieved by using the new orthosis. Thus, the present results emphasize the potential ambulatory benefits of the new orthosis.

Energy cost was not changed at the PWS-30%, while energy cost at the PWS+30% was significantly lower with orthosis after familiarization. The lack of significant changes at the lower speed may relate to the difference in step length. We hypothesize that the orthosis has effect only when there is a sufficient step length. A prerequisite for the orthosis to be effective is that the unaffected leg must be positioned far enough in front of the affected leg. Consequently, this leads to tension on the elastic straps of the orthosis, which guides the affected leg during the swing phase. Differences in walking speed are normally regulated through changing step length rather than the cadence. The diminished step length during the

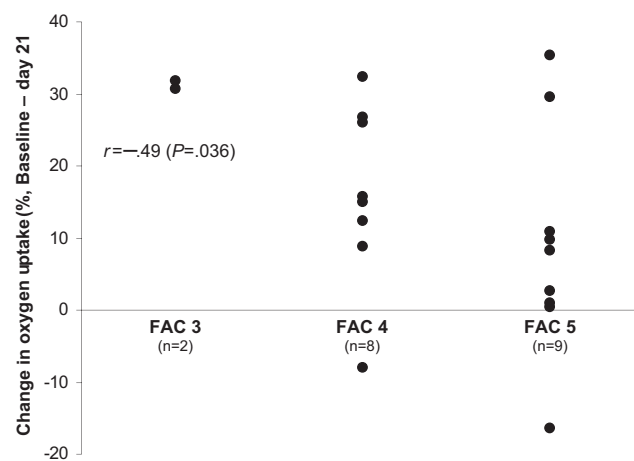


Fig 4. Correlation between FAC score and the relative change in energy cost between baseline and after 3 weeks of familiarization in persons with long-term hemiparetic stroke (n=19). For this between-subject correlation, energy cost was normalized to body weight. Values are mean ± SEM.

lower walking speed, therefore, leads to an insufficient tension on the elastic straps. This may underlie the lack of changes in energy cost at the lower walking speed.

Although no further improvement was found in the preferred walking speeds after 3 weeks of orthosis familiarization, energy cost reduced. A potential factor that could explain this change is the effect of training. However, one also expects the walking speed to change when observing a true training effect. For this reason, a training effect is an unlikely explanation of the further decrease in energy expenditure. We hypothesize that familiarization to the orthosis and an improvement in the tension of the straps (ie, adjustment of the whole orthosis) is the main cause for the reduced energy cost. The tension on the elastic straps is self-adjustable and participants were free to change the tension. This may have resulted in a more efficient way of walking.

A significant negative correlation is demonstrated between the FAC score and improvement in energy cost. This indicates that the persons with stroke with a lower FAC score (ie, more walking disability) have a larger benefit in energy cost using the orthosis. This is supported by the finding of a negative correlation between the preferred walking speed (which is tightly correlated with the FAC score) and the improvement in energy cost. This indicates that the persons with stroke with the lowest walking speed (and lowest FAC score) experience the largest benefit of the orthosis. Important to notice, however, is that subjects with a relatively high walking speed also can benefit from the orthosis.

Clinical Relevance

Due to the hemiparetic gait, stroke survivors develop a lower physical fitness. This new orthosis enables subjects to improve their gait and mobility. In the long term, this could increase physical fitness and the quality of life of persons with stroke. Since physical inactivity is an important cardiovascular risk factor,¹⁹ improvement of physical fitness may have a cardio-protective effect. In addition, 3 important advantages of the orthosis over the conventional AFO are present. First, an immediate effect is present using the new orthosis (without training or habituation). Second, the further improvement of gait pattern and energy cost after 3 weeks familiarization, while devices require prolonged periods (>4mo) and/or intensive rehabilitation,^{3,9,12} may suggest a large potential of the new orthosis. Third, no extensive gait training is needed to induce a clinically relevant improvement in gait pattern.

Study Limitations

A relatively large sample of the initial population did not complete the familiarization period. In addition to unforeseen problems (illness, hospitalization, burn wounds), the major reason for the dropout was that subjects were dependent on others to help put on the orthosis. We performed subanalysis of these persons with stroke that did not complete the familiarization period. At baseline, walking speed and oxygen uptake in these persons (1.5 ± 0.8 km/h and 45.7 ± 23.6 mL O₂/min, respectively) did not differ from the persons with stroke that finished the familiarization period (*t* test, *P* = .53; 1.3 ± 0.8 km/h; *t* test, *P* = .96; 46.3 ± 30.6 mL O₂/min, respectively). Despite the small population of dropouts (*n* = 8), they had during the baseline measurements a significantly higher walking speed using the orthosis (*P* = .01) and demonstrated a lower energy cost at the preferred walking speed (*P* = .03). The dropout is, therefore, unlikely related to a lack of physiologic efficiency of the orthosis (energy cost or walking speed). However, assistance

and/or supervision may be necessary for some chronic stroke survivors to benefit from the new orthosis.

CONCLUSIONS

The new orthosis immediately decreases energy cost and improves walking speed and step length in persons with stroke. After only 3 weeks of familiarization to the orthosis (without rehabilitation or gait training), energy cost and gait pattern are further improved. This suggests a high potential for this new orthosis to improve gait and decrease energy cost in long-term hemiparetic stroke survivors.

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- Suppliers**
- a. CVAid; Somas, Postbus 41, 5845 ZG Sint Anthonis, The Netherlands.
 - b. Motor-driven treadmill; Bonte BV, Ampèrestraat 25A, Zwolle, 8013 PT, The Netherlands.
 - c. Oxycon alpha; Jaeger Benelux BV, Rembrandtlaan 1B, Bilthoven, 3723 BG, The Netherlands.
 - d. GAITRite; SMS Technologies, Elizabeth House, Elizabeth Way, Harlow, Essex, CM19 5TL, UK.
 - e. Version 12.0; SPSS Inc, 233 S Wacker Dr, 11th FL, Chicago, IL 60606.