J Rehabil Med 2007; 39: 646–650

ORIGINAL REPORT

OXYGEN CONSUMPTION, OXYGEN COST AND PHYSIOLOGICAL COST INDEX IN POLIO SURVIVORS: A COMPARISON OF WALKING WITHOUT ORTHOSIS, WITH AN ORDINARY OR A CARBON-FIBRE REINFORCED PLASTIC KNEE-ANKLE-FOOT ORTHOSIS

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Objective: **To examine, for polio survivors, whether walking with a carbon-fibre reinforced plastic knee-ankle-foot orthosis (carbon KAFO) is more efficient than walking with an ordinary KAFO or without an orthosis.**
Design: **Consecutive sample.**
Setting: **Post-polio clinic, University Hospital of Occupational and Environmental Health, Kitakyushu, Fukuoka, Japan.**
Participants: **Eleven polio survivors who had a carbon KAFO prescribed at the post-polio clinic.**
Interventions: **A carbon KAFO was prescribed, fabricated and inspected.**
Main outcome measures: **Oxygen consumption, oxygen cost and physiological cost index.**
Results: **An ordinary KAFO weighed 1403 g (standard deviation(SD) 157 g), whereas a carbon KAFO weighed 992 g (SD 168 g). Subjects walking with a carbon KAFO showed a tendency to increase step length, and to increase speed significantly compared with walking without an orthosis and with an ordinary KAFO (paired *t*-test, $p < 0.05$). Oxygen consumption per body weight, oxygen cost (O_2 consumption for 1-m walk divided by body weight) and physiological cost index ((heart rate at 3-min walk – heart rate at rest) /speed) were significantly lower than those walking without an orthosis (–16%, –35%, –33%; paired *t*-test, $p < 0.05$) and were lower than those walking with an ordinary KAFO (–9%, –14%, –15%; paired *t*-test, $p < 0.05$).**
Conclusion: **The gait efficiency of polio survivors with a carbon KAFO was objectively better than those without an orthosis or with an ordinary KAFO.**

Key words: polio, knee-ankle-foot orthosis, carbon orthosis, oxygen consumption, physiological cost index.

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Submitted November 12, 2006; accepted April 25, 2007.

INTRODUCTION

Poliomyelitis is an acute generalized disease caused by poliovirus infection and is characterized by destruction of the motor cells in the spinal cord and brain-stem, and the onset of a flaccid paralysis of the muscles innervated by the affected neurones (1). Although there were epidemics of poliomyelitis in the 1940s and 1950s in the USA, and during 1949–51 and 1958–60 in Japan, new outbreaks have ceased in developed countries since the advent of an effective vaccine. About 30 years after the poliomyelitis epidemics, polio survivors are encountering new problems, including generalized fatigue, muscle weakness, pain in the lower extremities and back, and decreased functional capacity in daily and social life. These new problems are called post-polio syndrome, which is a neurological disorder that produces a cluster of symptoms in persons previously infected with poliomyelitis (2–7). Management of post-polio syndrome includes appropriate exercise, avoidance of muscular overuse, weight loss, use of a suitably light orthosis to eliminate excessive loads on the muscles of the lower extremities, use of assistive devices to maintain independence in daily and social life, and an alteration of lifestyle to cope with the new difficulties (6, 8).

A knee-ankle-foot orthosis (KAFO) or ankle-foot orthosis (AFO) is frequently prescribed for polio survivors with gait disturbance at our post-polio clinic, but some polio survivors with a KAFO or AFO often complain of their brace being "heavy when walking" and "uncomfortable to walk with", and of its "unattractive appearance." A recent development in the field of orthotics is a carbon-fibre reinforced plastic orthosis (abbreviated to carbon orthosis), and it may relieve those complaints arising from the use of an ordinary orthosis because a carbon orthosis is lightweight, durable and strong.

Carbon-fibre is a fibrous carbon material consisting of a minute graphite crystal structure, and is applied extensively to a wide variety of applications with superior mechanical characteristics. Nelham (9) applied carbon-fibre to prostheses and orthoses, and carbon orthoses have been prescribed for patients with myopathic (10), polio survivors (11–13) and

 ISSN 1650-1977
doi: 10.2340/16501977-0105

patients after stroke (14). Heim et al. (11) reported that carbon orthoses were 30% lighter than metal ones and that 70% of the post-polio patients were satisfied with their orthoses, and Steinfeldt et al. (12) demonstrated that the maximum walking distance of polio patients with a carbon orthosis significantly increased, partially due to a 40% reduction in weight, and 95% of the patients were very satisfied or satisfied. According to our previous report, which used visual analogue scales to describe walking in polio survivors (13), a carbon KAFO was lightweight, smart and slim, and safe and less fatiguing while walking.

Although Danielsson & Sunnerhagen (14) indicated that the use of a carbon AFO for patients after stroke resulted in a 20% increase in walking speed and a 12% decrease in energy cost while walking, it is not clear whether a carbon KAFO actually improves the gait efficiency of polio survivors more than an ordinary KAFO with double metal uprights. Therefore, we examined the gait efficiency of polio survivors walking without an orthosis, with an ordinary KAFO and with a carbon KAFO, by measuring oxygen consumption and the physiological cost index (15).

MATERIALS AND METHODS

The methods of prescription, fabrication and inspection of a carbon KAFO have been published previously (13), therefore we only briefly describe the subjects and methods in this paper. The subjects were 11 consecutive polio survivors (2 men and 9 women) who had a carbon KAFO prescribed, fabricated and inspected at our post-polio clinic, 7 of whom were diagnosed as having post-polio syndrome based on the given criteria (16). The subjects were 53.9 (standard deviation (SD) 9.8) years of age, and their onset of polio was at 1.5 (SD 0.8) years of age. Eight of the 11 subjects had been using an ordinary KAFO with double metal uprights for more than 10 years. At our post-polio clinic, 10 subjects were prescribed a carbon KAFO for a unilateral lower extremity, and one subject 2 carbon KAFOs for the bilateral lower extremities. Although a standard carbon KAFO consists of frames and sole moulded in carbon-fibre (616G2, Carbon Fiber Stockinette, Otto Bock Japan, Tokyo, Japan and CO1303, Carbon Fiber Fabrics, Toray Industries Inc., Tokyo, Japan) and acrylic resin (C-Orthocryl, Otto Bock Japan, Tokyo, Japan), pairs of Swiss lock knee joints and free ankle joints, we prescribed a solid ankle for 2 subjects who had undergone arthrodesis of their ankle joints, ring lock knee joints for one subject based on her personal preference, and off-set knee joints for the less-involved lower extremity of one subject using carbon KAFOs bilaterally.

Severity of paralysis was evaluated by a physiatrist at the clinic using the motor strength index (range 0–100) (17), which is the sum of scores from 0 to 5 of the Medical Research Council scales (18) for each major muscle in the bilateral upper extremities (deltoid, biceps, triceps, wrist extensor and hand intrinsic muscles) and the lower extremities (hip flexor, quadriceps, hamstring, dorsi-flexor and plantar-flexor muscles). Need for assistance in walking without an orthosis and with ordinary and carbon KAFOs was evaluated by a physiatrist using the functional ambulation category (19), which is a simple 5-point scale used to assess independence when walking: (1) continuous support, (2) intermittent support, (3) supervision, (4) independent on level ground only, and (5) independent anywhere. Basic capacity in daily life was evaluated using the self-rating modification of the Barthel Index (range 0–100) (20), and its reliability as a self-rating instrument had already been confirmed. Applied activities in daily and social life were evaluated using the self-rating modification of the Frenchay Activities Index (range 0–45) (21, 22), and its reliability as a self-rating instrument has been reported (22).

Oxygen consumption while walking without an orthosis, with an ordinary KAFO, and with a carbon KAFO was measured between 15.30 and 16.30 h using a telemetric breath-by-breath gas analyser (Meta Max 3b, Cortex Biophysik GmbH, Leipzig, Germany) at least one month after starting to use their carbon KAFO. According to the protocol based on the energy consumption study on comparing orthoses (23), the subjects were asked to walk along a 50-m rectangular line in the training room of our rehabilitation centre; the order in which they walked without an orthosis, with an ordinary KAFO, and with a carbon KAFO was randomly assigned to each polio survivor. An example of the protocol is as follows:

Resting phase: after a subject puts on a telemetric gas analyser with a heart monitor on the head and body, the subject sits on a chair for at least 10 min until both oxygen consumption and heart rate reach a steady state.

Standing phase: the subject stands up and waits 2 min before walking without a KAFO.

Walking phase: while the subject walks at the most comfortable speed for 5 min, oxygen consumption and heart rate are continuously monitored. A physiotherapist counts the number of steps and measures the walking distance while walking alongside the subject and being conscious of safety.

Recovery and standing phase: the subject sits on a chair and puts on an ordinary KAFO. After the oxygen consumption and heart rate recover to a steady state, the subject stands up again, and waits 2 min before walking with the ordinary KAFO.

Second walking phase: the subject walks with the ordinary KAFO as in the protocol. *Recovery and standing phase:* the subject changes the ordinary KAFO to a carbon KAFO and waits 2 min.

Third walking phase: the subject walks with the carbon KAFO as in the protocol.

Final phase: the subject sits on a chair and removes the equipment.

The oxygen consumption and heart rate values were averaged for the last 30 seconds of each walking phase.

The subjects were permitted, if necessary, to use a cane or crutches, but we cancelled the measurement of walking without an orthosis if they needed any help or were at risk of falling. During the measurement of walking with an ordinary KAFO, they walked with their previous KAFO, which they had been using before completion of their carbon KAFO, after an orthotist adjusted the ordinary KAFO to obtain a good fit.

Oxygen consumption per body weight was defined as O_2 consumption for one min divided by body weight (ml/min/kg), and oxygen cost was defined as O_2 consumption for 1-metre walk divided by body weight (ml/m/kg).

The physiological cost index is a simple measurement of gait efficiency (15), which is often used to evaluate a prosthesis and orthosis, and is obtained from the formula: (heart rate (beats/min) at 3-min walk – heart rate (beats/min) at rest) divided by speed (m/min). The physio logical cost indexes for walking without an orthosis, with an ordinary KAFO and with a carbon KAFO were calculated from the heart rates at rest and at 3 minutes after walking, as shown on the telemetric heart monitor, and measuring the distance walked in 3 min.

The data obtained were stored in a spreadsheet created using commercial software, and the differences between walking without an orthosis and with a carbon KAFO and between walking with an ordinary KAFO and with a carbon KAFO were analysed with SPSS 8.6J software, using the Wilcoxon matched-pairs signed-ranks test or the paired t-test. p-values less than 0.05 were regarded as significant, and p-values less than 0.1 and more than 0.05 were regarded as showing a tendency. Conforming to the Helsinki Declaration, we obtained informed consent from all subjects, who voluntarily joined in this study, after one of the authors (FW) explained the purpose, methods and protection of personal information orally and in writing.

RESULTS

Patients' profile and KAFO

The motor strength index score was 70.6 (SD 11.6) in total, 46.6 (SD 5.2) for the upper extremities, and 24.0 (SD 8.2) for the lower extremities. The Barthel Index score was 95.1 (SD 9.9), and the Frenchay Activities Index score was 25.1 (SD 7.2). The ordinary KAFO weighed 1403 (SD 157) g on average, whereas the carbon KAFO weighed 992 (SD 168) g, with an average reduction weight of 411 (SD 129) g.

Walking with a KAFO

Eight of 11 subjects completed the measurement of walking without an orthosis, as this measurement was cancelled halfway through for 3 subjects who were at risk of falling. Eight of the 11 subjects participated in the measurement of walking with an ordinary KAFO, with 3 subjects not participating because they had neither used nor possessed an ordinary KAFO. All subjects participated in the measurement of walking with a carbon KAFO, which fitted well, and they had already become accustomed to using it.

Nine of the subjects needed continuous or intermittent support while walking without an orthosis; the median of the functional ambulation category scores for walking without an orthosis was 2.0, and its mode was 1. All subjects walking with both KAFOs showed a significant increase in scores of the functional ambulation category compared with walking without an orthosis (Wilcoxon matched-pairs signed-ranks test, $p < 0.05$), but there was no significant difference between walking with an ordinary KAFO and with a carbon KAFO (Wilcoxon matched-pairs signed-ranks test, $p > 0.05$): 3.5 for median and 3 for mode while walking with an ordinary KAFO; 4 for median and 5 for mode while walking with a carbon KAFO.

Gait efficiency

There were no significant differences in the number of steps per min between walking without an orthosis and with a carbon KAFO, and between walking with an ordinary KAFO and with a carbon KAFO (paired *t*-test, $p > 0.05$). Step length while walking with a carbon KAFO showed a tendency to increase by 15% compared with walking without an orthosis, and by 11% compared with walking with an ordinary KAFO (paired *t*-test, $p=0.05\text{-}0.1$). Speed while walking with a carbon KAFO was significantly faster (27%) than that while walking without an orthosis, and significantly faster (11%) than that while walking with an ordinary KAFO (paired *t*-test, $p < 0.05$; Table I).

Oxygen consumption per body weight (ml/min/kg), oxygen cost (ml/m/kg), and physiological cost index while walking with a carbon KAFO were significantly lower than those while walking without an orthosis (–16%, –35%, and –33%, respectively; paired *t*-test, $p < 0.05$) and were significantly lower than those while walking with an ordinary KAFO (–9%, –14%, and –15%, respectively; paired *t*-test, $p < 0.05$).

DISCUSSION

Because the number of subjects in this study was small, the study design was a single centre trial, and the physiological cost index may be less valid as a measure of the energy cost of walking (24), the results of the study may have some limitations. However, the subjects were not intentionally sampled, and all results of the oxygen consumption per body, oxygen cost and physiological cost index clearly indicated differences in gait efficiency between walking without an orthosis, with an ordinary KAFO and with a carbon KAFO.

According to the results of the functional ambulation category, a carbon KAFO improved independence of walking as well as an ordinary KAFO, but this scale did not have sufficient sensitivity to distinguish between walking with a carbon KAFO and an ordinary KAFO. From our previous subjective study, the carbon KAFO was lighter in weight, fitted better, and gave more support than the ordinary KAFO, and was regarded as safer and less fatiguing (13). This objective study on gait efficiency revealed that the oxygen consumption per body weight, oxygen cost, and physiological cost index in walking with a carbon KAFO were less than those in walking either without an orthosis or with an ordinary KAFO, and we believe that the carbon KAFO subjectively and objectively improves the gait efficiency of polio survivors.

Table I. *Gait efficiency. Data is given as mean with standard deviation.*

	Without orthosis vs with carbon KAFO		With ordinary KAFO vs with carbon KAFO	
Steps per min, *n*	77.0 (12.5)	84.3 (13.2)	92.9 (6.3)	92.0 (11.1)
Step length, cm	39.7 (7.5)	45.6 (7.0)**	41.3 (7.0)	45.7 (8.2)**
Speed, m/min	31.0 (8.6)	39.5 (9.8)*	38.5 (7.0)	42.6 (7.8)*
Oxygen consumption per body weight, ml/min/kg	13.5 (4.7)	11.4 (2.7)*	14.0 (3.2)	12.8 (2.4)*
Oxygen cost, ml/m/kg	0.46 (0.16)	0.30 (0.09)*	0.37 (0.08)	0.32 (0.09)*
Physiological cost index	1.07 (0.47)	0.72 (0.44)*	0.95 (0.36)	0.81 (0.43)*

Without orthosis: 8 of 11 subjects completed the measurement of walking without an orthosis.
With ordinary KAFO: 8 of 11 subjects participated in the measurement of walking with an ordinary KAFO; the 3 subjects who did not participate had neither used nor possessed an ordinary KAFO.
With carbon KAFO: 11 subjects completed the measurement of walking with a carbon KAFO.
KAFO: knee-ankle-foot orthosis; SD: standard deviation.
Paired *t*-test; $*p < 0.05$ $**p < 0.1$

A carbon KAFO improves the gait efficiency of polio survivors, possibly because it is lightweight and it fits well. The carbon KAFO used in this study is about 29% lighter than the ordinary KAFO containing double metal uprights, as it was reported that the weight reduction was 30% by Heim et al. (11) and 40% by Steinfelt et al. (12). The weight reduction, which may be negligible in healthy adults, probably improved gait efficiency by relieving polio survivors with severe muscle weakness from excessive motions or muscular overload of the trunk and lower extremities while walking. A well-fitting KAFO may also contribute to an improvement in gait efficiency. If the KAFO is slim and smart, and fits well, polio survivors feel the lightness of the KAFO during the swing phase, and the good fit may increase the number of steps per min and/or step length to some degree while walking with the carbon KAFO. In this study, walking with a carbon KAFO increased the step length and significantly increased the speed compared with walking with an ordinary KAFO, and, consequently, walking with a carbon KAFO may be more efficient for polio survivors than walking with an ordinary KAFO.

Although the number of steps per minute for walking with ordinary and carbon KAFOs were more than that for walking without an orthosis, there was not a significant difference among the 3 groups, possibly because of wide individual variation. The steps per minute and speed in the column of "without orthosis vs with ordinary KAFO" shown in Table I were somewhat less than those in column for "with ordinary KAFO vs carbon KAFO". The reason may be as follows. The 3 polio survivors who cancelled halfway through the measurement of walking without an orthosis could walk with a carbon KAFO at a faster speed than average. Therefore, the deletion of the 3 pairs of measurements may have decreased the averaged speed while walking with a carbon KAFO.

Because the carbon KAFO has obvious advantages (lightweight, durable, slim, smart, and efficient in walking) (11–14), it is positively indicated for patients with muscle weakness induced by lower motor neuron lesions, especially polio survivors (11–13). However, some issues remain to be resolved. In Japan, a carbon KAFO is 50% more expensive than an ordinary KAFO (13). The carbon KAFO cannot be modified after completion (11, 13), because the acrylic resin used for the carbon KAFO is not thermoplastic after polymerization. As the first step, we make a temporary KAFO made of polypropylene, and spend several weeks inspecting and modifying the temporary KAFO, and as the second step, we fabricate a carbon KAFO based on the temporary KAFO (13). A new thermoplastic material containing carbon-fibre may solve this problem. A carbon KAFO itself is sufficiently durable, but some parts used for the carbon KAFO are not as durable as carbon-fibre reinforced plastic. New knee and ankle joints that are sufficiently durable and light should be developed for a carbon KAFO. If we find a solution to these issues, the carbon KAFO will become more popular for all patients with disabilities.

In conclusion, oxygen consumption per body weight, oxygen cost and physiological cost index while walking with a carbon KAFO were significantly less than those obtained either without an orthosis or with an ordinary KAFO, indicating that the carbon KAFO improved the gait efficiency of polio survivors.

ACKNOWLEDGEMENTS

Part of this paper was presented at the 41st Annual AAP Educational Conference, the Association of Academic Physiatrists, February 2004, Tucson, USA.

This study was supported by a contribution to Hachisuka's research grant.

The clinical study was performed in co-operation with Saburo Ohmine, RPT, at the Rehabilitation Center, University Hospital of Occupational and Environmental Health, and with Mitsuo Arai, CPO, and Kenji Arai, CPO, at Arai's PO Ltd.

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