Prosthetics and Orthotics International, 1990, 14, 103–110

Performance of three walking orthoses for the paralysed: a case study using gait analysis

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Abstract

Three types of walking orthosis are currently available to enable paralysed people to achieve reciprocal gait. This case study assesses the performance in walking of one patient who was proficient in the use of all three devices. The results of a biomechanical analysis are presented in which comparisons are made between the orthoses in terms of general gait parameters and movement of the lower limbs and pelvis.

Introduction

In recent years a considerable amount of time, effort and money has been directed towards permitting paralysed people to walk again using reciprocal gait. Stallard *et al.* (1989) noted that of the three approaches currently under development (mechanical orthoses, functional electrical stimulation, and hybrid devices which combine the first two alternatives) only the first, using purely mechanical orthoses, is clinically viable at the present time, and even this has its limitations. However, continuing research and corresponding advances in medical technology mean that the future may hold many exciting new developments, with corresponding benefits to the paraplegic person.

During the last few years two designs of walking orthosis have emerged as practical systems. The hip guidance orthosis (HGO) or "ParaWalker" (Fig. 1a) was developed by Gordon Rose and his colleagues at the Orthotic Research and Locomotor Assessment Unit, Oswestry, England (Rose, 1979). The reciprocating gait orthosis or RGO (Fig. 1b) was developed by Roy Douglas with his colleagues at Louisiana State University (Douglas *et al.*, 1983). More recently a third design, a development of the RGO system, has emerged from Hugh Steeper Ltd, London, and is henceforward referred to as the Steeper's orthosis (Fig. 1c).

As far as locomotion is concerned, the general principles of all three orthoses are similar. The body is braced from the mid-trunk to the feet, with knees and ankles immobilised. The hips are allowed to flex and extend, but are prevented from moving into adduction when the leg is lifted off the ground. Walking is achieved by pulling the trunk forward, using crutches or rollator, then tipping the pelvis so that the trailing leg is lifted clear of the ground, thus allowing it to move forward and take a step. The hip joints on the HGO are free to flex and extend between stops, whereas on the RGO there are twin cables linking the two sides so that extension on one side causes flexion on the other. On the Steeper's orthosis the hip mechanism is a modified version of that in the RGO, but using only a single cable, encased in a steel tube. The use of only one cable should have the effect of reducing friction.

In response to the pressure from patients wishing to be provided with walking orthoses, following considerable publicity given by the media to one particular paraplegic, the Department of Health and Social Security in the United Kingdom commissioned an extensive, comparative trial of the HGO and RGO which spanned almost two years and was carried out at the Nuffield Orthopaedic Centre, Oxford. Some 22 patients were given the opportunity to use each orthosis for a period of 4 months in a crossover

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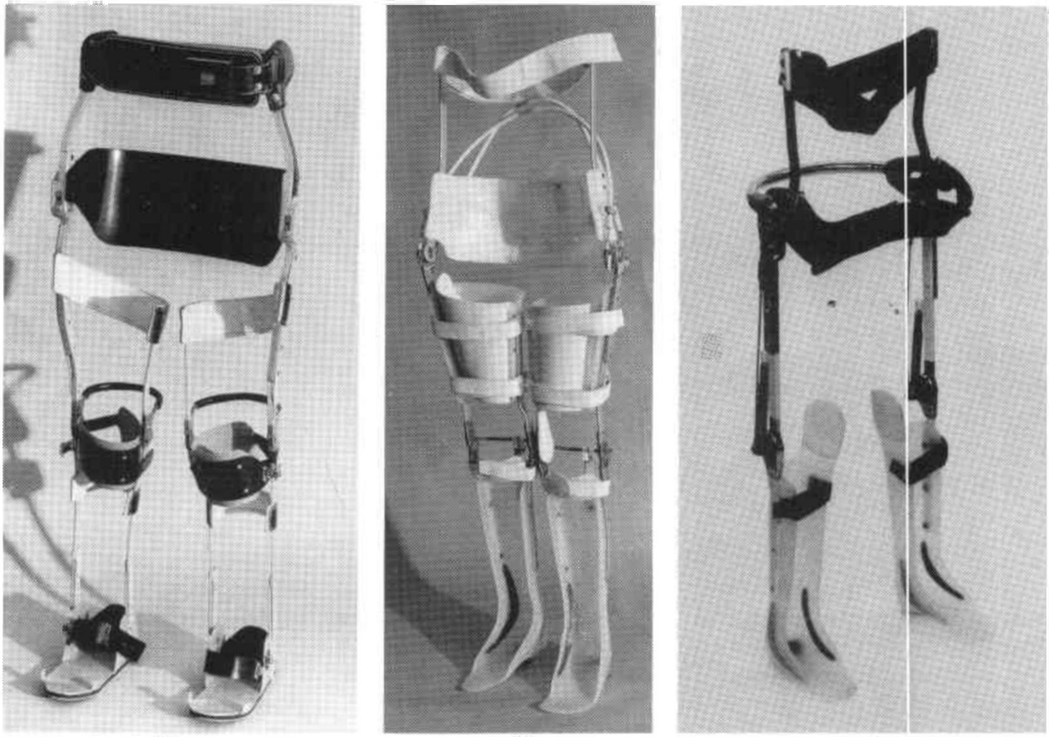

(a) (b) (c)

Fig. 1. The orthoses used in the study:—
a) Hip Guidance Orthosis, b) Reciprocating Gait Orthosis, c) Steeper's Orthosis.

study. Clinical, ergonomic, biomechanical, psychological and economic assessments were performed at appropriate stages on each patient who completed the trial. Full details of the comparisons made and the results obtained were contained in the published report (Whittle and Cochrane, 1989). Inter-subject differences were much greater than inter-orthosis differences, but the biomechanical assessments did demonstrate that the patterns of movement were not identical in the two orthoses.

The Steeper's orthosis has only just become available, so that it has not been the subject of any independent assessment. Its major advantage over either of the other two devices is the ease it confers upon rising from a sitting position, and, conversely, upon sitting down again after standing. In the Steeper's orthosis standing can be performed directly from a normal flexed knee sitting position, without prior manual straightening of the legs and locking of the orthotic knee joints which is required in both the RGO and HGO. An additional source of energy is provided for these movements by the use of springs mounted on the above-knee side members, which provide a knee extension moment to assist in standing and control of hip flexion in sitting down. The hip joints and knee joints are connected via cables, so that the hip mechanism releases the knee lock. It is possible for the orthotist to set the tension in the springs to the correct level for each individual patient to achieve standing and sitting with ease.

The patient in this case study had already participated in the comparative trial of the HGO and RGO, and was consequently a proficient user of both orthoses. He had also become involved in the trials of the prototype Steeper's orthosis, and thus was in the unique position of having used all three devices. With his cooperation it was possible to perform gait analysis to enable biomechanical comparisons to be made of the three orthoses in terms of the general gait parameters and the movements of the lower limbs and pelvis.

Methods

Subject

The subject for the case study was a 33-year-old man (height 1.76m, weight 72kg) with complete motor and sensory paraplegia below T5 segmental level as a result of a motorcycle accident five years previously. He was otherwise fit, his only regular medication being Baclofen (20mg three times daily) to control extensor spasticity present in both his legs. After his accident, he had been fitted with Hip Knee Ankle Foot Orthoses, and although he could stand in these with the aid of crutches, he was unable to walk with them. He first attended the Nuffield Orthopaedic Centre in November 1986, when he was selected to participate in the comparative trial of the HGO and RGO. His determination to succeed led to his achieving a considerable degree of proficiency in both orthoses. Ultimately he chose to keep the RGO.

Subsequent to this he became involved in the manufacturer's trial of the prototype Steeper's orthosis, and consented to attend the Oxford Orthopaedic Engineering Centre once again so that biomechanical assessments of his gait wearing all three devices could be performed.

Assessments

Two methods of biomechanical assessments were used – conventional videotape and the Vicon motion analysis system. The former was used to determine the general gait parameters (cadence, stridelength and velocity) by means of a stopwatch and markers at known positions on the floor.

The Vicon television/force platform/ computer system was used for the full biomechanical assessment. Retroflective markers were attached to whichever orthosis was being worn, at the levels of mid-foot, ankle, knee, hip, and front and back of the trunk support. These showed up as bright spots in the field of view of four television cameras, when illuminated by strobes mounted close to the lens of each camera. The cameras were interfaced to a PDP 11/23 minicomputer. The system was calibrated to give the three-dimensional location of each of the reflective markers at 20ms intervals, to an accuracy of 3-4mm in all three directions (Whittle, 1982 and 1986). Data were recorded during two walks at free speed with each orthosis. The subject first used the RGO with a rollator, followed by the Steeper's orthosis with the same rollator, and, finally, the HGO with crutches. He used his normal walking aid, whether rollator (RGO and Steeper's orthosis) or crutches (HGO). Unfortunately, it was not possible to assess the proportion of force passing through the walking aid due to problems with instrumenting the rollator. In addition, no attempt was made to obtain valid force platform data as this would have involved considerably greater problems for the patient. The kinematic data were subsequently analysed to determine the detailed linear and angular movements of the braced lower limbs and pelvis. The processed data from the two walks with each orthosis were combined to give average values of the relevant parameters. The general gait parameters were calculated and compared with those obtained from the videotape measurements. Other important biomechanical parameters studied included the range of motion of hip joints in both the flexion/extension and adduction/abduction axes, and the movements of the pelvis both up and down and side to side.

Results

General gait parameters

Table 1 lists the values of these parameters for each of the orthoses used. Measurements were made both from the videotape and from the

Table 1. General gait parameters using all three orthoses.

Parameter	Units	Normal Range	RGO	Steeper's orthosis	HGO
cadence	steps/min	91–135			
(video)			39	39	34
(Vicon)			35	37	37
stride length	m	1.25–1.85			
(video)			0.99	0.99	0.84
(Vicon)			1.02	0.99	0.98
velocity	m/s	1.10–1.82			
(video)			0.32	0.31	0.24
(Vicon)			0.30	0.31	0.30
stance phase	%	54–65	67	67	73

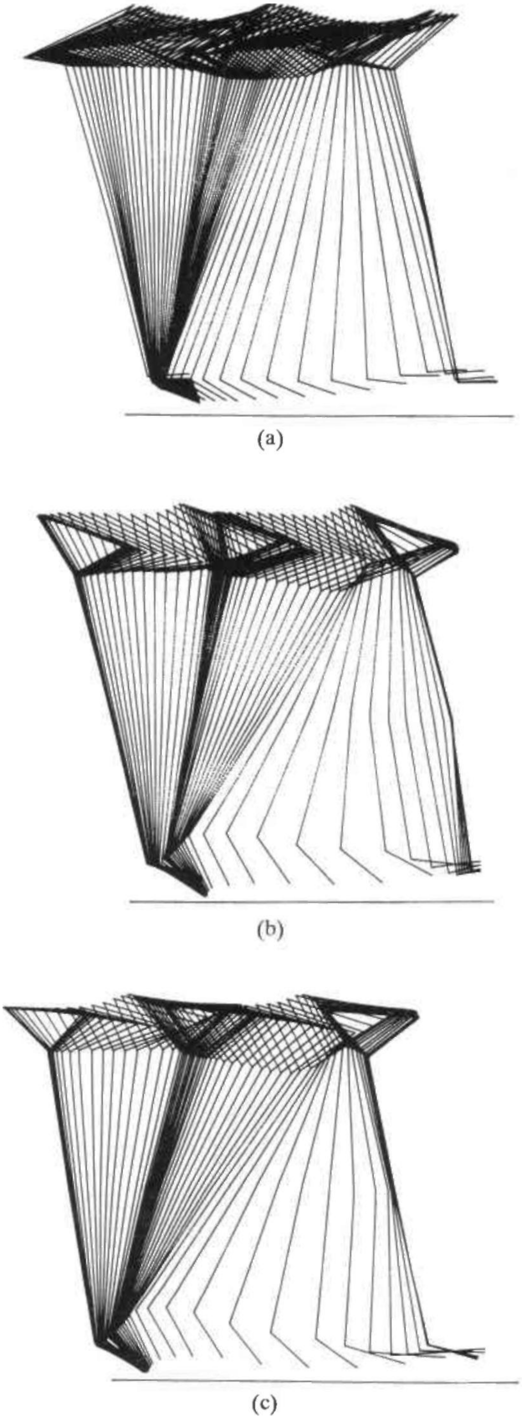

Fig. 2. Sagittal plane motion in all three orthoses:—
a) HGO,
b) RGO,
c) Steeper's orthosis.

Vicon data. The normal ranges are derived from young men measured in our laboratory (Kirtley *et al.*, 1985). Differences are small and, despite acclimatisation time, are possibly attributable to the patient's greater degree of familiarity with the RGO and Steeper's orthosis, both of which he used regularly at home.

Pattern of Movement

Figure 2 (a, b, c) shows a sagittal plane representation of the position of the right leg and pelvis plotted at 60 ms intervals during a single gait cycle from heelstrike to heelstrike in each orthosis. Scaling factors are constant. Features of note are:—

i) a similar stride length in all three cases,
ii) a smaller range of pelvic motion and a different mean antero-posterior tilt in the HGO,
iii) a more jerky pattern of movement in the RGO and Steeper's orthosis, appearing as widely spread lines when the legs are moving faster, and more crowded lines when the movement slows down.

In the transverse plane the pelvis twists forwards and backwards about the vertical axis in the HGO, whereas in the RGO and Steeper's orthosis it remains fairly straight throughout the cycle.

Hip joint motion

Table 2 gives the ranges of hip joint motion in both the sagittal and coronal planes in all three orthoses. The angles refer to the maximum recorded angle between the vertical and the line joining the hip and the ankle markers in the appropriate plane.

Sagittal plane:— Both the RGO and Steeper's orthosis demonstrated a greater range of motion than the HGO, because of the smaller degree of hip extension in the latter. The hips flexed similarly in all three devices, although flexion in

Table 2. Hip joint motion using all three orthoses. All angles measured in degrees.

Parameter	RGO	Steeper's orthosis	HGO
SAGITTAL PLANE			
Flexion	15	12	16
Extension	33	35	21
Range of motion	48	47	37
CORONAL PLANE			
Adduction	8	10	7
Abduction	3	0	9
Range of motion	11	10	16

the Steeper's orthosis was slightly less than in the RGO, with a corresponding increase in extension to maintain the overall similarity of range. In all three orthoses the foot did not contact the ground until the hip had reached full flexion and started to extend again. In the RGO and Steeper's orthosis there was a hesitation after heelstrike, at the time when the rollator was moved forwards, whereas the pattern in the HGO was more regularly sinusoidal.

Coronal plane:— Figure 3 (a, b, c) compares the degree of abduction at that stage in the gait cycle, when the hip joint is in neutral sagittal plane alignment. In the HGO the legs remain essentially parallel and this alignment is not affected by load: adduction of the weight-bearing limb is equal to abduction of the swinging limb. In the RGO, and even more so in the Steeper's orthosis, the degree of adduction during weight bearing is greater than the degree of abduction during the swing phase (Table 2).

Angular motion:— Table 3 lists the magnitudes of the angular motions of the pelvis in the sagittal, coronal and transverse planes ("pitch", "roll" and "yaw" respectively) for each orthosis. The expected similarity between the RGO and Steeper's orthosis is further borne out: both differ quite markedly from the HGO. The total sagittal plane angular excursion in the HGO was less than in the other orthoses, and the pelvis moved along a smooth sinusoid. In the RGO and Steeper's orthosis the basic motion was sinusoidal, but with a plateau intercalated while the rollator was being advanced. The peaks of the sinusoid corresponded with the peak extension and flexion of the hips. In the coronal plane the pelvis was raised on the side of the swing phase leg in each orthosis. The greatest differences, affecting both

Table 3. Pelvic translations and angular motion in all three orthoses.

Parameter	RGO	Steeper's orthosis	HGO
LINEAR MOTION			
vertical excursion (mm)	46	43	22
lateral excursion (mm)	90	80	152
ANGULAR MOTION			
sagittal plane, "pitch" (deg)	16	17	11
coronal plane, "roll" (deg)	16	17	12
transverse plane "yaw" (deg)	23	26	33

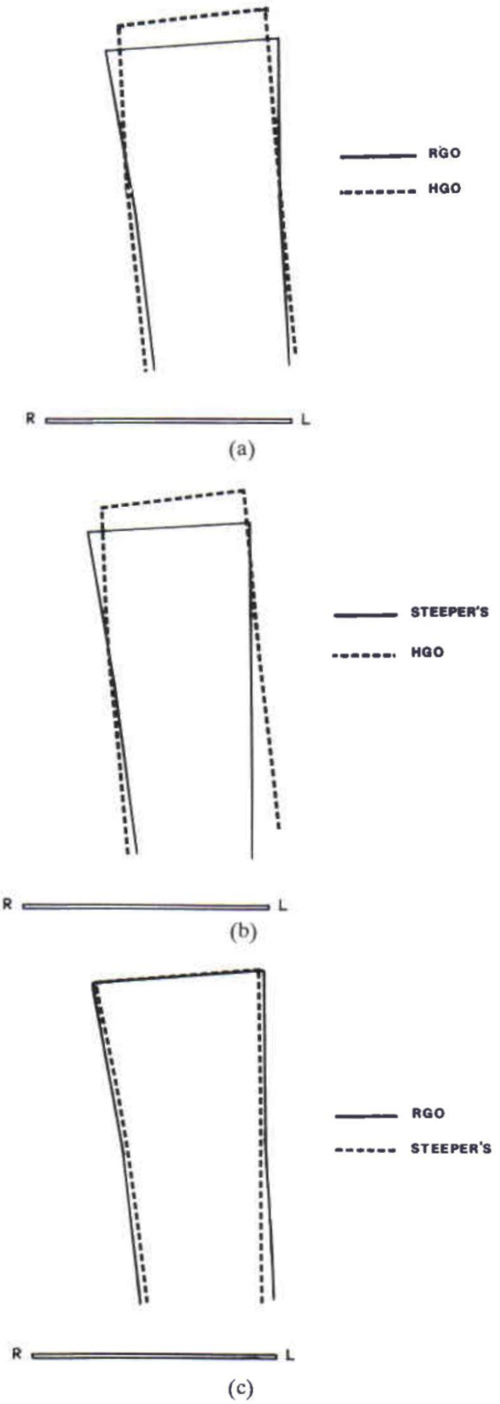

Fig. 3. Comparisons of all three orthoses at similar stages in the gait cycle in the coronal plane:—
a) HGO vs RGO,
b) HGO vs Steeper's orthosis,
c) RGO vs Steeper's orthosis.

the magnitude and phasing of the movement, were observed in the transverse plane. In the HGO the twisting of the pelvis from side to side in a sinusoidal pattern had a much greater amplitude than in either the RGO or Steeper's orthosis. In these devices, higher frequency oscillations were superimposed on the basic sinusoid, once again due to the pattern of movement with the rollator; both sides of the pelvis tended to be advanced together.

Pelvic translations:— The vertical excursion of the centre of the pelvis in the HGO was approximately half its observed value in the other two orthoses. It also followed a more gently undulating sinusoidal path. Peak values in all three orthoses were attained during the swing phase on each side. The centre of the pelvis had a larger lateral excursion in the HGO and its locus was almost a pure sinusoid, compared with a more complex pattern in the RGO and Steeper's orthosis. In all three cases the maximum excursion was away from each leg during its swing phase.

Pelvic velocity:— The velocity in the direction of progression attained a maximum in the middle of the swing phase and a minimum just after heelstrike, irrespective of device. However, the range of velocity variation did differ between orthoses. The HGO showed a variation in forward velocity between 0.15m/s and 0.45m/s, compared with a range of 0.05m/s to 0.63m/s in the RGO and of 0.01m/s to 0.59m/s in the Steeper's orthosis. These results give further evidence of a stop-start pattern in the RGO and Steeper's orthosis; in the latter device there is an instant in the cycle when the pelvis is virtually stationary.

Discussion

It could be argued, with some justification, that the comparisons in this paper are more accurately between the different systems (orthosis plus walking aid) than between the devices themselves. The walking aids were those specified in the training directions for each orthosis, and were, therefore, those the patient would be expected to use with the particular device. Familiarity with the system should produce a better gait, and for the purposes of this study was thus allowed to override the scientific advantages of restricting the patient to using the same walking aid with each system. It has not been possible in the present study to ascertain the significance of the different aids, though the small differences observed in the general gait parameters (Table 1) would suggest that the effect on the speed of walking may not be very great.

In the sagittal plane the major differences in hip joint motion between the respective orthoses is the smaller degree of hip extension in the HGO. The increased pelvic rotation, however, neutralises any consequent difference in stride length. In the RGO and Steeper's orthosis, the stride length is achieved almost entirely by the degree of flexion/extension at the hip joints. It is surprising that these two orthoses are so similar, as far as sagittal plane motion is concerned, since the reduction in friction from the use of a single cable in the Steeper's orthosis should permit an increased range of hip movement.

The observation that the hip abduction in the HGO is greater than that in either the RGO or the Steeper's orthosis has important implications with regard to ground clearance during the swing phase. In the HGO it is easier to clear the ground without catching the swinging leg behind the stance leg. Whittle and Cochrane (1989) noted this as probably the most important mechanical difference between the HGO and RGO, and one which makes the HGO more suitable for use with crutches. The present case study further bears out this observation. The reason for the difference is undoubtedly the greater degree of flexibility of both the RGO and Steeper's orthosis, compared with the HGO. On examination, the Steeper's orthosis was found to be slightly more flexible than the RGO; this would explain the absence of abduction during the swing phase. In the Steeper's orthosis, ground clearance is achieved almost entirely by elevation of the pelvis.

Thurston *et al.* (1981) measured the angular displacements of the pelvis in the sagittal, coronal and transverse planes in 22 normal subjects. The angular displacements in the present study differ markedly from their results in both magnitude and pattern. In all three orthoses, there is an increased 'roll' which may be associated with the compensations necessary to gain foot clearance in a stiff-legged gait (Saunders *et al.,* 1953). The greater than normal "yaw" in the HGO is an exaggeration of the normal mechanism whereby pelvic twisting is used to increase the stride length. With the arms fixed by the crutches, the contraction of latissimus dorsi pulls the pelvis upwards and twists it forwards. This twisting movement continues into stance until after the toe-off on the opposite (swing) side, whereupon it is rapidly reversed to impart some acceleration to the swinging leg. In the RGO and Steeper's orthosis, the maximum forward twisting of the pelvis occurs at the time of the corresponding heelstrike.

The variations in the vertical excursion of the centre of the pelvis in the different devices can also be associated with the different patterns of movement observed. In the RGO and Steeper's orthosis, both sides of the pelvis tend to be advanced together, which will necessitate a greater elevation of the pelvis, achieved by pushing down on the rollator, to permit forward progression. It results in a more jerky movement.

The other notable difference between the RGO and the Steeper's orthosis is the variation of the velocity in the direction of progression. The motion is better sustained in the RGO than in the Stepper's orthosis, for which there is an instant in the gait cycle when the pelvis is momentarily stationary, giving an additional contribution to the jerky motion already observed. Neither of these devices, however, achieves the smoothness of the HGO.

On the basis of the smaller pelvic movement in the HGO, it would be expected that the energy cost of walking in this orthosis would be less than in either of the other two devices. In this case study, however, energy expenditure was not measured, since it is difficult to make accurate measurements, and the results of the comparative trial (Whittle and Cochrane, 1989) do not suggest that there is an important difference in energy consumption between the HGO and the RGO.

The study would have been enhanced by the addition of kinetic data, although considerable difficulties would be involved in its acquisition. The aim of the study was to measure the patient's natural gait in each orthosis using the recommended walking aid, without imposing any additional constraints. The relatively short step length would make it very difficult to acquire "clean" data, with one foot per force platform, and there is also a strong possibility of recording a mixture of contact by the foot and the walking aid. In addition, it is very undesirable that the patient should "aim" for the force platforms.

Conclusions

Similar patterns and magnitudes of motion were observed in both the RGO and the Steeper's orthosis. Important biomechanical differences were noted in:—

i) swing phase hip abduction and, therefore, in the way in which ground clearance was achieved,
ii) the variation of velocity in the direction of progression: the pelvis was momentarily stationary at a particular instant in the gait cycle in the Steeper's orthosis, contributing to a more jerky motion.

The major difference between the two, however, appeared not in the walking performance but in standing up and sitting down. The inclusion of a compression mechanism in the Steeper's orthosis made sitting and standing much easier, with corresponding advantages to the patient both socially and in terms of energy expenditure at the beginning and ending of a walk.

The HGO showed marked differences from the other two devices, viz:—

i) a smaller variation of forward velocity, and a greater smoothness of the fore- and aft-movements,
ii) the subject's legs remained essentially parallel in the coronal plane, giving better ground clearance,
iii) a smaller range of sagittal plane motion, the compensation for which is a greater degree of pelvic twisting.

In this study we have concentrated on objective measurements, to the exclusion of other important factors such as cosmesis and ease of donning and doffing, which significantly influence the choice of the individual patient. However, in order to improve the design and function of future devices, an understanding of the biomechanics of movement in those currently available is essential. This paper is offered as a step towards this goal.

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