this could not be evaluated with the present limb design.

The outcome of this study indicates that weight distribution in the prosthetic shank/foot has a significant impact on gait. This suggests that future prostheses should be designed to minimize distal shank/foot weight.

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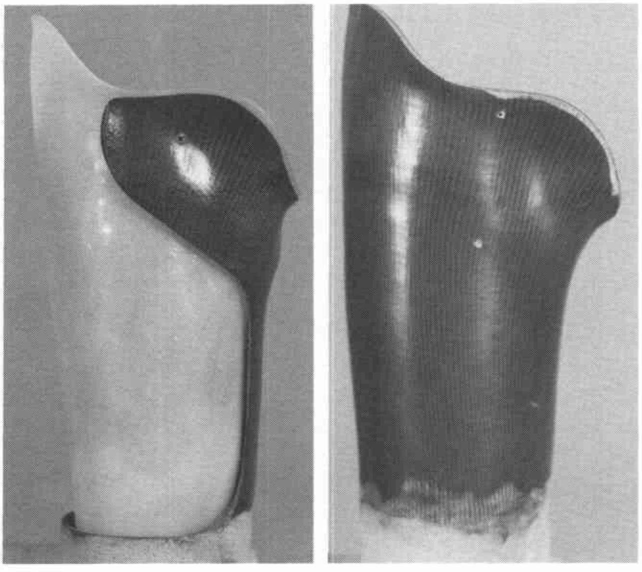
Kinematic and Kinetic Comparison of the Conventional and ISNY Above-Knee Socket

by David E. Krebs, M.A., P.T. Scott Tashman, M.S.

Prosthetic sockets must be comfortable, but they must also be functional. Despite advances in other prosthetic components, the materials used to construct the portion of the prosthesis that most directly contributes to amputee comfort, the socket, have remained essentially unchanged since the introduction of thermosetting resin sockets in the 1950's.[1–4]

A prosthetic socket must perform at least two functions: it must contain the stump tissues, and during stance phase, it must provide a means of transferring the amputee's weight from the pelvis and residual limb to the floor. To contain the stump tissues, the socket shape encourages optimal distribution of forces and pressure, during both swing and stance phases. Body weight is transmitted primarily from the ischial tuberosity to the proximal brim of the socket, through the vertical socket walls, and finally through the knee, shank, and foot to the floor.[5]

Conventional sockets surround the entire residual limb with rigid thermosetting resins, thus requiring this single container to perform both socket functions. The rigid proximolateral socket wall has been reputed to provide stabilization for the residual limb,[3] although no em-



Figures 1A and 1B. The ISNY Socket System.

pirical evidence has been reported to substantiate this claim.

The ISNY socket system (Figure 1) has been introduced recently by facilities in Iceland, Sweden, and New York University. The ISNY system consists of two parts, each with its own function. The ISNY socket is flexible, but not elastic, and biomechanically only serves to contain the stump tissues. This containment, of course, thus provides an inelastic reaction point for the thigh and the muscles that act upon it. The ISNY frame consists of a strong thin strut located horizontally around the quadrilateral brim, and vertically along the medial portion of the prosthetic thigh section,[6,7] that performs the weight transfer function. Because the strut is extraordinarily strong, more than 75 percent of the residual limb is covered only by the soft flexible thermoplastic.

Over 1,000 amputees world-wide have been fitted with the ISNY socket. These amputees consistently report significant improvement in prosthetic comfort. No amputees have complained of instability due to the flexible lateral wall of the ISNY, nor have clinicians reported functional disadvantages stemming from the flexible ISNY socket. On the contrary, even amputees who have been converted from pelvic band suspension on a conventional hard socket to solely suction suspension with an ISNY socket, show no visually apparent gait instabilities.

The purpose of this single-subject study is to objectively investigate the kinematic and kinetic differences during walking in an ISNY and a conventional socket. In particular, we sought to answer the question: "Does the absence of a rigid lateral wall, such as in the ISNY socket, contribute to gait instability?"

METHOD

This investigation provided a single, unilateral above-knee amputee with two thigh sections, one with an ISNY and the other with a conventional socket, and then analyzed selected kinematic and kinetic gait variables during walking at a slow speed, a preferred rate, and a fast speed, to determine if biomechanical differences resulted during walking in the two different sockets.

Subject

A thirty-six year old male participated in this single-subject research design. He provided written, informed consent prior to participation. The subject, a left above-knee amputee since a motor cycle accident 12 years prior to the study, is an otherwise healthy, active non-athlete who is employed in a full-time job that demands at least eight ambulatory hours daily. The subject is 1.75 m (5 feet, 9 inches) tall and weighs 104 kg (229 lb.); his residual limb length is 80 percent of the right (normal) femur. The subject wears an above-knee exoskeletal prosthesis with SACH foot, Mauch S-N-S hydraulic knee, and quadrilateral total-contact suction socket.

Prosthesis

Two types of above-knee prosthetic sockets, identical in size, shape, and alignment, were made for the components described above. The sockets were fitted to interchangeable thigh sections, to permit easy exchange of the conventional and ISNY sockets upon a single shank section.

One socket was fabricated of conventional rigid thermosetting resins, while the other was of ISNY construction. The subject had worn a conventional socket from the time of amputation until initiation of this investigation. At that time, the conventional socket was duplicated using Plaster-of-Paris to fabricate a positive model, which in turn was utilized to construct the ISNY socket. Both types of prosthetic sockets therefore provided identical total stump contact.

Because alignment symmetry is such an important determinant of prosthetic gait, the thigh-to-shank alignments and weight-transfer lines on the prosthetic thigh sections were precisely duplicated utilizing laboratory bench-alignment techniques.[3] In addition, alignment was visually inspected while the patient stood and walked in both sockets; adjustments were made until the alignments were symmetrical. Following prosthetic fabrication, however, no further alignment alterations were possible, thus helping to insure the integrity of the data collection procedures.

Testing Procedure

Both ISNY and conventional sockets were tested during the same day, to minimize variability in gait laboratory data collection techniques, and differences within the subject that longer between-analysis trials might have entailed. The conventional socket had been worn for 12 months; the ISNY socket had been worn for the 11 months immediately prior to gait analysis. The subject wore each type of prosthesis at least two hours immediately prior to testing, to permit re-accommodation to the prosthesis to be tested.

Both sockets were tested while the subject walked at one of three self-selected speeds. The testing order for socket type and walking speed was randomly assigned; walking speed order was replicated over the sockets. One of the following commands was given to the amputee prior to each experimental run:

1. "Walk as slowly as you comfortably can"
2. "Walk at your normal pace"
3. "Walk as fast as you comfortably can"

The exact speed at which the subject chose to walk under the three different commands was self-selected: no attempt was made to interpret the commands, or to interfere with the amputee's self-selected speed during data collection on the first socket. Prior to walking trials with the second socket to be tested, the subject was instructed to attempt to duplicate the speed at which he walked with the first type of socket.

Each socket/speed combination was tested twice to assess the kinematic stability (reliability) of the test situation.

Data Collection

Kinesiological data was collected at the Gait Laboratory of Newington Children's Hospital, Newington, Connecticut, one of the most technologically sophisticated gait data collection centers in the United States. The gait lab and data collection are described in detail elsewhere.[7-9] In this study, the following data was simultaneously monitored and subsequently displayed:

Kinematics: Joint positions of the pelvis and both lower-limbs in three dimensions.

Kinetics: Floor reaction forces and moments of the prosthetic side in three dimensions.

Data collection was conducted identically for all experimental conditions. Furthermore, the amputee was "blind" to the experimental hypotheses; the data collection techniques were designed to obviate experimenter bias.

Data collection began after the amputee had taken at least three steps, to insure that steady-state walking velocity had been achieved.

Kinematic Data

The following joint motions on the amputated and the sound sides were measured:

Hip: Extension/flexion, abduction/adduction, and internal/external rotation;

Pelvis: Sagittal tilt, frontal plane obliquity and transverse rotation;

Knee: Extension/flexion; valgus/varus; and internal/external rotation;

Foot: Plantar/dorsiflexion and transverse rotation.

In addition, the following events were obtained: cycle time; toe off, heel off, and prosthetic stance duration in percent cycle time; stride and step length in cm.; cadence in steps per minute; and overall velocity (walking speed) in meters per second.

Passive, optically reflective limb position markers were placed on the prosthetic side over the posterior sacrum, anterior superior iliac spine, greater trochanter of the hip, lateral mid-thigh, lateral knee, lateral mid-shank, ankle lateral heel, and the lateral foot at the level of the fifth metatarsal head. Similar markers were placed on the subject's sound side. The markers remained in place between runs, with the exception of the markers placed on the experimental thigh sections, which were re-attached in identical positions for both types of sockets.

Prior to data collection, it was specified that output differences of five degrees or more, in any plane during stance phase, were to be accepted as significant departures from kinematic symmetry of the two socket systems. Particular attention was to be paid to residual limb hip and pelvic motions, because the prosthetic knee and foot motions cannot be affected by socket differences.

Kinetic Data

Ground reaction forces and moments generated by the amputee while walking in the two sockets were measured by two six-channel force plates. The force plates have a 12 bit resolution, and output X (antero-posterior), Y (medio-lateral), and Z (vertical) force and moment signals proportional to the ground reactions during the gait cycle. The force plates are sampled at 2 KHz, and low-pass filtered with a 300 Hz. fourth-order Bessel analog filter to dampen high frequency noise.

The force plates are mounted flush with the floor and are thus totally unobtrusive; the subject was neither made aware of their location, nor instructed to alter his gait to strike the force plates.

Prior to data collection, it was specified that differences of five percent or more were to be accepted as significant departures from kinetic symmetry. Particular attention was to be paid to residual limb medio-lateral force and shear kinetics, because alterations in the medio-lateral support of the socket would be most likely to be revealed by changes in these force-plate variables.

RESULTS

Gait analysis was performed first on the ISNY socket, followed by analysis of the conventional socket. The walking speed randomization resulted in the following trial sequence: preferred pace, then slow pace, then fast pace walking. Temporal data for each run is presented in Table 1. Kinematic and kinetic data resulting from the two sockets and three walking speeds are given in Figures 2 through 5.

No differences of greater than five degrees are found in any of the stance phase kinematics, with the single exception of late stance phase hip rotation at slow walking speed. This isolated finding is probably insignificant.

Test-retest reliability analyses revealed no more than two to three degrees difference, for any given speed, between repeated runs in the same socket.

DISCUSSION

No substantial kinematic or kinetic differences are to be found in the analysis of this subject's biomechanical data. Therefore, socket design did not differentially affect the subject's gait timing, joint motions, or forces. In particular, it would appear that the absence of a rigid lateral wall does not adversely affect dynamic stump or pelvic stability of this above-knee amputee.

It is important to note the limitations of single-subject research design. Although it is quite reasonable to infer that this subject's gait was unchanged (or more precisely, differed by less than expected error amounts) in the two types of prosthetic sockets, it would be incorrect to generalize the results of this study beyond this single subject. That is, it is possible that kinematic differences might be found in other subjects, despite their absence in this subject.

Temporal Comparisons No consistent pattern was found with regard to between-socket comparisons of walking speed, nor stance duration, nor any other important temporal variable (Table 1). For example, walking velocity in the conventional rigid socket was about eight and 13 percent faster than in the ISNY at "fast" and "slow" walking speeds, respectively, but velocity is about one percent greater at the self-selected "preferred" walking speed. Prosthetic stance phase duration was consistently, if only slightly, longer with the ISNY socket, than with the conventional socket, approaching near-normal values at the "fast" velocity. This finding agrees with the data from Murray and colleagues.[10] It is possible, therefore, that the ISNY socket permitted greater stance-phase comfort, which in turn permitted more normal

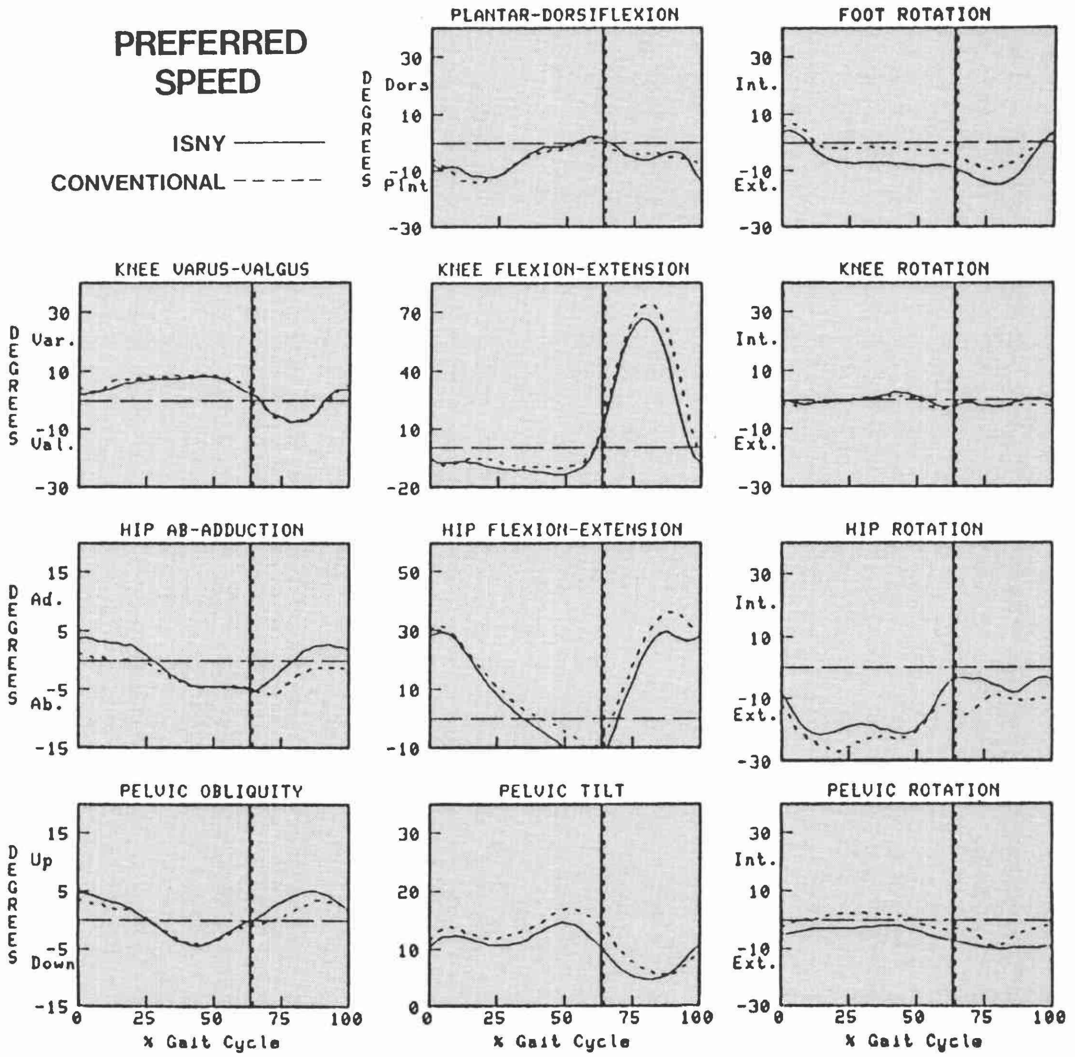


Figure 2.

weight acceptance during stance phase than with the conventional socket. That is, the ISNY socket appeared to permit more symmetrical prosthetic to sound side stance durations. Leavitt, et. al.[11] support the contention that more comfortable sockets permit longer, and more normal, stance phase durations.

Kinematic Comparisons No kinematic between-socket differences of greater than five degrees were found, except in "slow" walking hip rotation. The latter finding probably reflects normal, minor variability in walking kinematics.[12] Kinematic variability, at least in non-amputees, is greater at non-preferred walking cadences.[13] Of particular interest to this study is the fact that hip abduction in the ISNY socket was relatively invariant over the three walking velocities, and indeed, more closely approximated previously reported kinematics from normal subjects[14] than did the subject's hip kinematics while walking with the conventional socket.

Kinetic Comparisons Normal subjects walking at self-selected comfortable speeds exert vertical floor reactions that increase from 0 to approximately 120 percent of body weight from heel strike to foot flat. As the knee flexes in midstance and then extends in preparation for push-off, vertical forces decline to 60 to 80 percent, then increase to a second peak of about 120 percent of body weight, falling again to 0 after toe-off.[15-19]

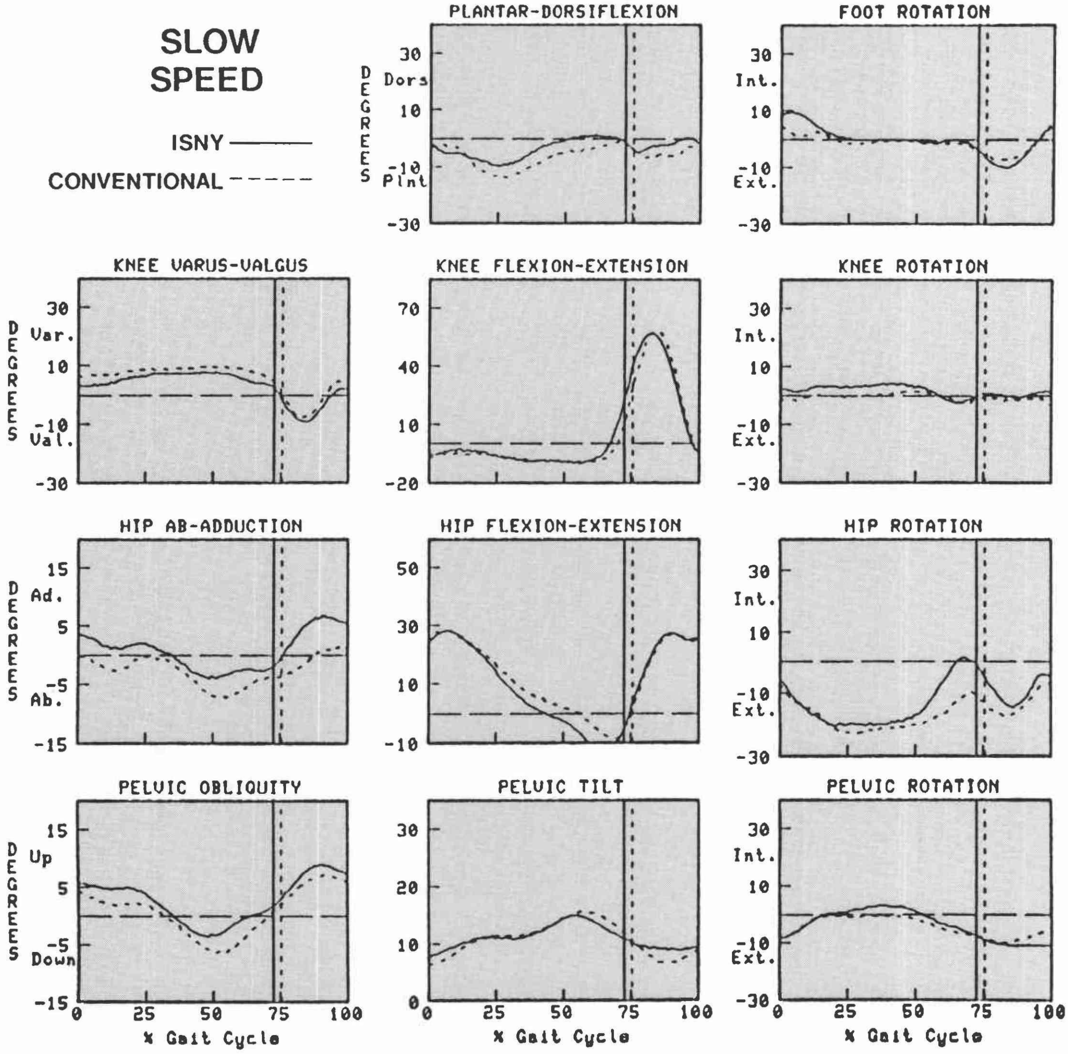


Figure 3.

The kinetic data reveal no medio-lateral differences between the ISNY and the conventional socket. With respect to vertical forces, the ISNY appears to have been loaded more quickly, and more forcefully, during "preferred" and "fast" walking than was the conventional socket. Again, this result can probably be attributed to the greater comfort of the ISNY socket, which permitted the amputee to load the limb in a more normal pattern than was the conventional socket.

General Observations Several general features of this amputee's gait are also noteworthy. Examination of the kinematic plots of knee joint motion during stance phase reveals that the knee is in hyperextension, under all walking conditions. That is, the knee bolt was set quite posterior to the hip and ankle, despite the recommendations from as long ago as 1954 that above-knee amputees with residual limbs as long as this patient's should probably not have the knee bolt offset posteriorly.[2,20] The kinetic plots indicate the unfortunate effect of this alignment stability: the floor reaction vector remains in front of the prosthetic knee even during late stance, when the amputee is attempting to roll over the keel of the SACH foot to begin knee flexion. Thus, the prosthetic limb is excessively stable, which substantially increases the work required for locomotion in comparison with an optimally aligned limb.

The fact that the prosthetic knee remained in

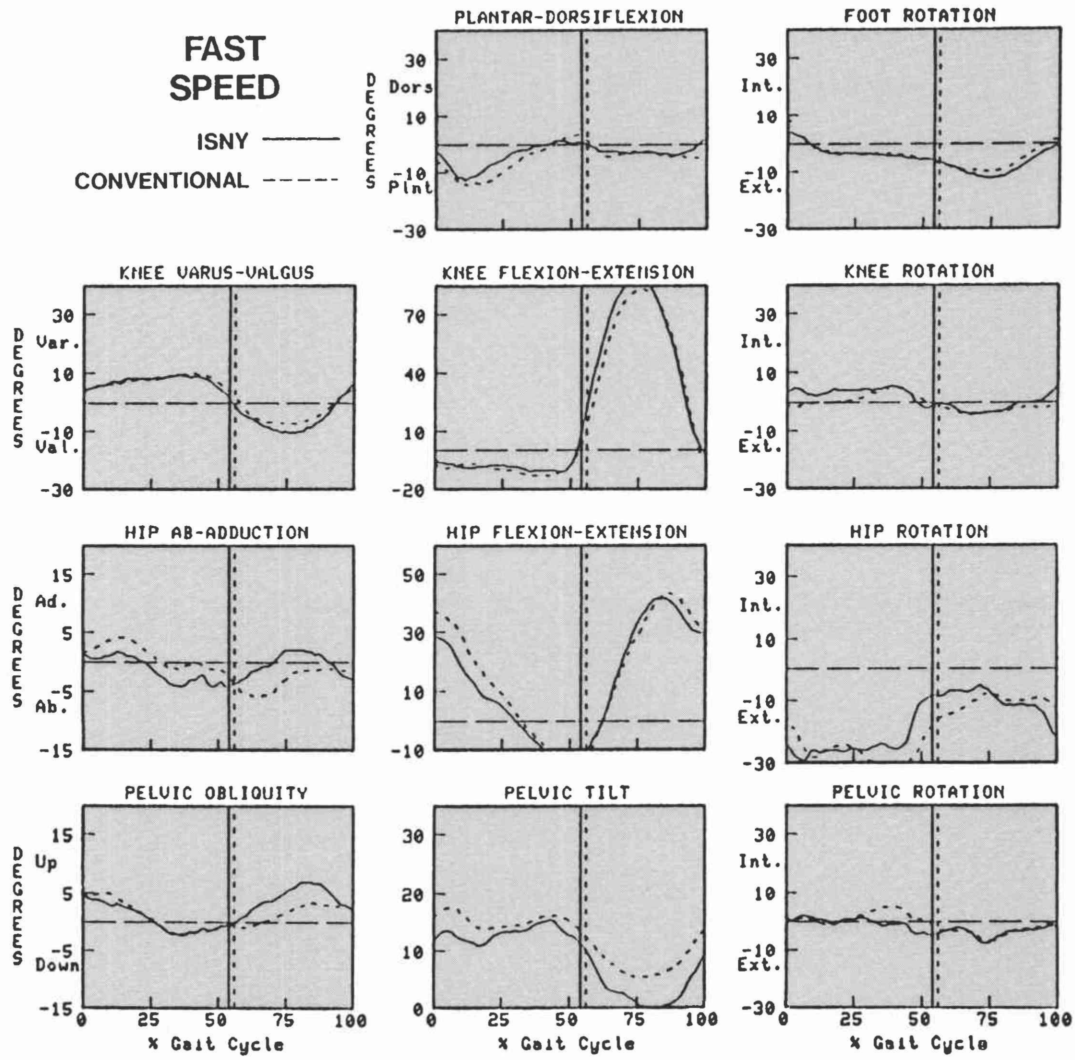


Figure 4.

varus throughout stance phase no doubt reflects appropriate inset of the foot and shank. It is therefore not surprising that the pelvic obliquity kinematics and the medio-lateral kinetics rather closely approximate normal values.

SUMMARY

In summary, no important temporal, kinematic or kinetic differences were found during this single-subject comparison of an ISNY and a conventional rigid above-knee prosthetic socket. Indeed, we have speculated that these gait laboratory data may provide evidence of a functional advantage of the ISNY, with respect to stance phase duration and loading of the prosthesis. Therefore, given no functional disadvantage of the ISNY and given that the subject finds the ISNY to be significantly more comfortable, it may be concluded that the overall evidence favors use of the ISNY socket. Firm conclusions, however, must await further studies that compare comparably fitting ISNY and conventional sockets in larger groups of amputees.

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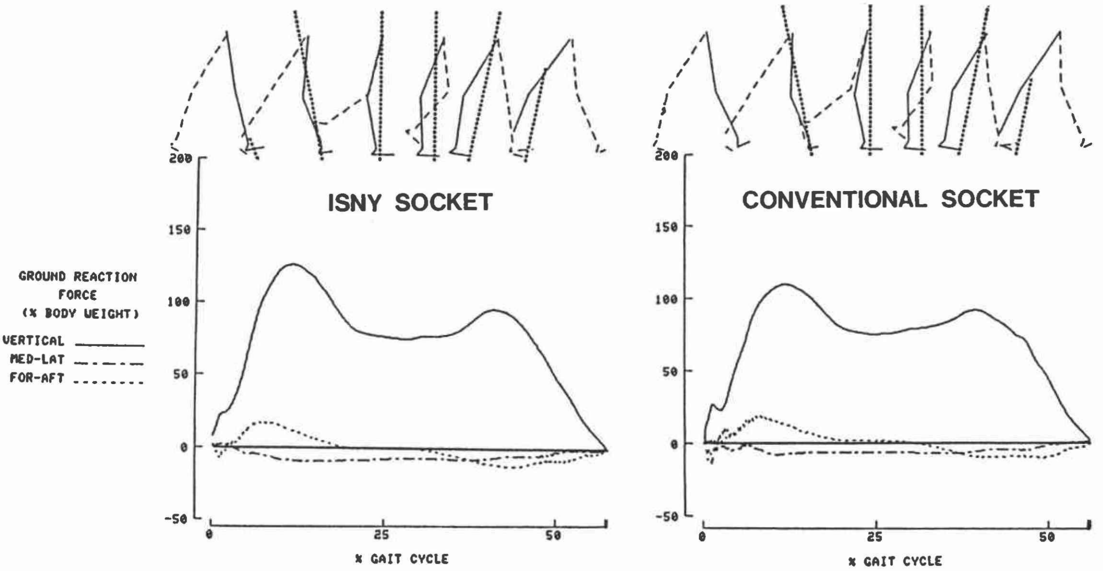

Figures 5A and 5B.

	ISNY Socket			Conventional Socket		
	Slow	Preferred	Fast	Slow	Preferred	Fast
Toe-off (% of Gait Cycle)	72.2	63.4	54.0	75.7	64.6	56.1
Opposite Toe-off (%)	27.7	17.1	9.5	29.7	16.5	12.1
Opposite Heel-strike (%)	55.5	51.2	46.0	55.0	50.6	47.0
Single Stance (%)	27.7	34.2	36.5	25.2	34.2	34.9
Step Length (cm)	53.3	64.1	74.9	53.2	65.4	75.7
Stride Length (cm)	112.3	130.9	152.7	107.2	129.5	147.0
Cycle Time (sec)	1.7	1.4	1.1	1.9	1.3	1.1
Cadence (steps/min)	70.3	86.7	112.5	65.2	88.4	107.5
Walking Speed (cm/sec)	65.7	94.6	143.2	58.2	95.3	131.6

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The Application of Gait Analysis in Orthotics

by Robert S. Lin, C.P.O.

A gait analysis laboratory is an invaluable tool in the quantitative analysis of orthotic systems and their effect on human locomotion. This is particularly true in cases where the orthotic design is based on biomechanical behavior of the extremity during gait, as in the anterior floor reaction orthosis, the posterior offset knee mechanism and the Scott-Craig orthoses.

Traditionally, the success or failure of an orthosis has been based on clinical observation by the orthotist, physician or therapist, while relying on the latest medical record entry and their recollection of the patient's status. Even the most comprehensive dictations often fail to note important subtle factors.

On the other hand, a gait lab report provides a formal permanent record of the specific gait status of an individual. This detailed analysis can be reviewed any time.

Clinical application of the gait laboratory is best demonstrated in the management of an 11 year old spastic diplegic at Newington Children's Hospital. M.C. came to us with hip flexion contractures, bilateral knee flexion contractures, and equinovarus deformities of both feet. Despite these lower extremity contractures, he is ambulatory, exhibiting a markedly tenuous gait pattern and unable to stand in place.

Computerized gait analysis was performed pre-op and ten weeks post-op with and without the anterior floor reaction orthoses. In addition to the stick figures and ground reaction data, linear measurement of single stance percentage, stride length, walking velocity, and external work of walking were all obtained.

These results provided quantitative pre-op, post-op, and post-op with orthoses data which compared specific differences in gait behavior and the effects of surgery and orthotic management on these.

In addition to comparative studies of pre-op, post-op and post-op with orthoses conditions,