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WALKING SPEED AS A BASIS FOR NORMAL AND ABNORMAL GAIT MEASUREMENTS*

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Abstract—Gait observations of normal subjects and patients with knee disabilities are presented. Time–distance measurements and ground reaction force parameters are reported in relation to walking speed. Regression analysis is used to establish simple functional relations between ground reaction force amplitudes and walking speed.

It is shown that basic time distance measurements observed over a range of walking speeds can be useful indicators of gait abnormalities associated with knee disabilities. For example, clinical improvement after treatment is found to be consistent with changes in these gait parameters. These results indicate the usefulness and importance of considering gait measurements in relation to walking speed when attempting to classify gait abnormalities.

INTRODUCTION

Modern joint replacement surgery has placed new requirements on our knowledge of the mechanics of human locomotion. The incidence of failures due to mechanical origin indicates the need for a better understanding of the biomechanical factors associated with gait.

Studies of human gait are inherently complex because the parameters that can be observed on a subject when walking are interrelated. For example, several studies have shown that many gait parameters are velocity-dependent Grieve (1966) reported on the relationship between time-distance parameters and walking speed. Other investigators (Murray *et al.*, 1966, Lamoreux, 1971, and Cavanagh and Gregor, 1975) have reported that angular limb motion, muscular activity and joint reactions are dependent on walking speed. Jacobs *et al.* (1972) have demonstrated changes produced in the frequency content of the vertical component of the foot–ground reaction due to differences in the inertial contribution at different walking speeds.

A number of investigators including Murray *et al.* (1972), Sutherland *et al.* (1969), Stauffer *et al.* (1975), Perry *et al.* (1974), and Chao (1975) have reported observations of subjects with gait abnormalities. One particular feature observed among all subjects with diseased joints is a slower than normal walking speed. Thus, when quantitating gait abnormalities one should distinguish which variations from normal walking patterns are due to differences in walking speed and which are due to gait abnormalities.

The purpose of this investigation was to examine two types of gait parameters (temporal and ground reaction force) obtained from normal subjects and patients with knee joint disabilities. A procedure is described which allows observations over a range of normal walking speeds. The results of temporal and foot–ground reaction force measurements are reported graphically in terms of their relationship to walking speed and on that basis comparisons are made among the various observations between normal subjects and patients with knee disabilities.

MATERIALS AND METHODS

Subjects observed

Seventeen normal subjects ranging in age from 22 to 59 yr (average 28 yr), in height from 155 to 180 cm (average 173.0), and in weight from 436 to 1050 N (average 757.0 N) were observed on two separate occasions in the gait laboratory. Sixteen subjects with knee pathologies ranging in age from 48 to 76 yr (average 65 yr), in height from 154 to 178 cm (average 165 cm) and in weight from 730 to 980 N (average 770 N) were also observed.

A clinical diagnosis indicated 11 patients had degenerative arthritis while five had rheumatoid arthritis. Nine patients had unilateral and 7 had bilateral knee involvement. Twenty knees were treated with total joint replacement and three were treated with high tibial osteotomies.

Thirty-four gait observations were made on 16 subjects with knee disabilities consisting of 11 just prior to surgery, 14 observations an average of 4.4 months after surgery and 8 observations an average of 8.9 months after surgery. All patient observations were categorized as gait patterns of subjects with knee disabilities.

Measurement protocol

A single gait observation included as many as 20 traverses of a 10 m walkway. Each subject was asked to walk a prescribed number of times at his normal walking speed, fast walking speed and slow walking

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speed. Normal subjects and patients with knee disabilities were measured following identical protocols. Measurements on normal subjects were repeated. Patients were observed preoperatively and at specified intervals postoperatively.

Time–distance measurement

Average forward velocity was derived from the on-off closure of a series of five photocells placed at 2.5 m intervals along the walkway. Velocity was computed for each 2.5 m intervals. Cadence, time of support and time of swing were measured using instrumented foot pads placed inside the subject's shoes.

The instrumented foot pad consisted of an insole with a cluster of pressure sensitive transducers located at the heel, fifth metatarsal, first metatarsal and big toe. The on–off closure pattern from four transducers on each foot were transmitted through a cable attached to an overhead trolley which trailed the subject while walking.

The on–off closure pattern from the foot switches and five photocells was combined into a 13-bit digital word and sampled at the rate of 100 Hz. Each bit was decoded in the computer to provide times of switch closures and openings as well as photocell timing for velocity calculation.

Time of swing, time of support and dual support time were derived for each limb independently from the on–off closure patterns of the foot switches. Time of swing was defined as the amount of time all switches were open, time of support was defined as the amount of time any combination of switches were closed, and dual support time was defined as the time when any switches on both feet were simultaneously closed during one cycle. The times were averaged over one traverse of the walkway (usually *ca.* 5 strides) for which the subject was walking at uniform velocity. Thus, 20 traverses of the walkway yielded 20 times of swing, support and dual support for the left and right limbs over a complete range of walking speeds. Average cadence and stride length were also derived from foot switch and photocell measurements.

Ground reaction force measurements

A Kristal piezoelectric force plate (40 × 60 cm), mounted inconspicuously in the center of the walkway, was used to measure dynamically the three components: foot–ground reaction force, vertical twisting moment and center of pressure. However, only the three components of force (medial-lateral (X), fore-aft (Y), and vertical (Z)) were analyzed in this study. The analog signals from the force plate were digitized at a sample rate of 200 Hz and processed with a digital computer.

To avoid alterations in normal walking patterns subjects were not given specific instructions to step on the force plate. A typical test involving 20 traverses of the walkway would produce *ca.* 10 adequate steps on the measuring surface. Ground reaction force measurements were recorded with temporal measurements on magnetic tape for further processing.

Data analysis

As described above, both temporal and ground reaction force data were collected over a spectrum of walking speeds. A two-dimensional approach was used to analyze these gait observations. Each parameter was analyzed in terms of its parametric relationship to walking speed. Data were interpreted and compared by observing each parameter plotted against walking speed. A least square regression analysis was used to fit linear, quadratic, and cubic polynomials to each data set.

Each traverse of the walkway at a uniform walking speed produced a single data point for each of the temporal and ground reaction force parameters. A gait observation consisted of the combined measurements obtained from every traverse of the walkway (usually 20) taken in one session.

Data from each gait observation were plotted as illustrated in Fig. 1. Comparisons among observations were made by comparing an entire curve rather than a single measurement. Both temporal and force plate parameters were analyzed using this two-dimensional approach.

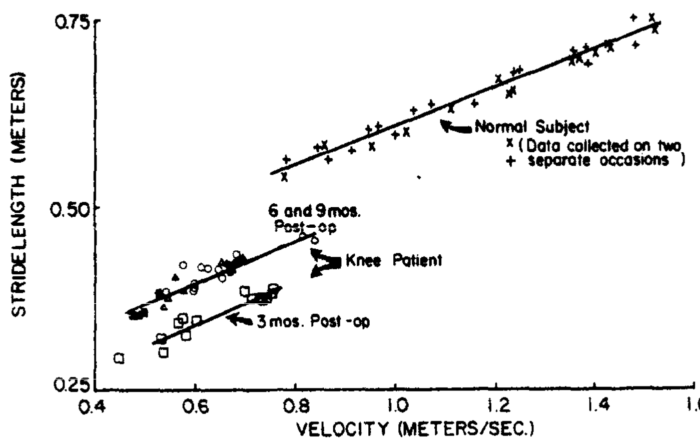

Fig. 1. An illustration of the steplength–velocity relationships for a normal subject and a patient treated with a total knee replacement.

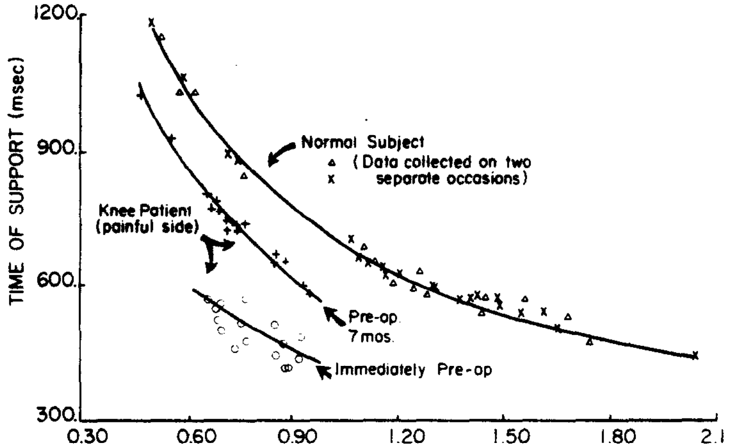

Fig. 2. An illustration of the time of swing–velocity relationships for a normal subject and patient treated for a total joint disability.

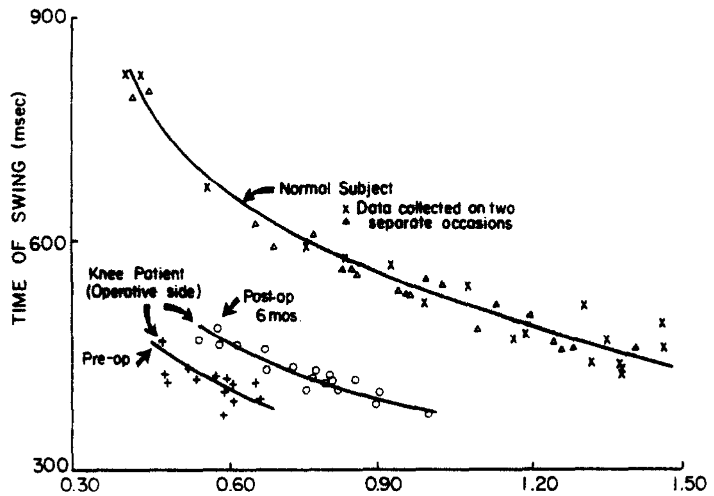

Fig. 3. An illustration of the time of support–velocity relationships for a normal subject and a patient treated with a total knee replacement.

RESULTS

Normal gait patterns

Steplength, cadence, times of swing and support were observed to change in characteristic and repeatable manners with changes in walking speeds. As observed by other investigators (Grieve 1966, and Lamoreux, 1971), steplength and cadence varied linearly with forward walking speed for normal subjects. Typical relationships between steplength and walking speed are illustrated in Fig. 1. An increase in walking speed for normal subjects was achieved by uniform and characteristic changes in both steplength and cadence.

Time of swing and time of support were found to be inversely proportional to walking speeds (Figs. 2 and 3). The curves of these parameters against forward walking speed were approximated best by quadratic polynomials. As a subject increased his walking speed, a decrease in both time of swing and time of support was observed.

Time–distance measurements were found to be reproducible for normal subjects when the entire velocity relationships were considered. As illustrated in Figs. 1–3, curves of the velocity relationship of time–distance measurements taken on two separate occasions were found to superimpose for the normal subject.

The time varying components of the ground reaction forces are illustrated in Fig. 4. The waveform of the lateral, fore–aft and vertical force were characterized by 9 amplitudes. The lateral components were characterized by an initial amplitude ($X1$) at heel strike, a second maximum amplitude ($X2$) at foot flat and a third amplitude ($X3$) at toe-off. The fore–aft component of force was characterized by an initial amplitude ($Y1$) posteriorly directed at heel strike, a second amplitude ($Y2$) anteriorly directed, and a third

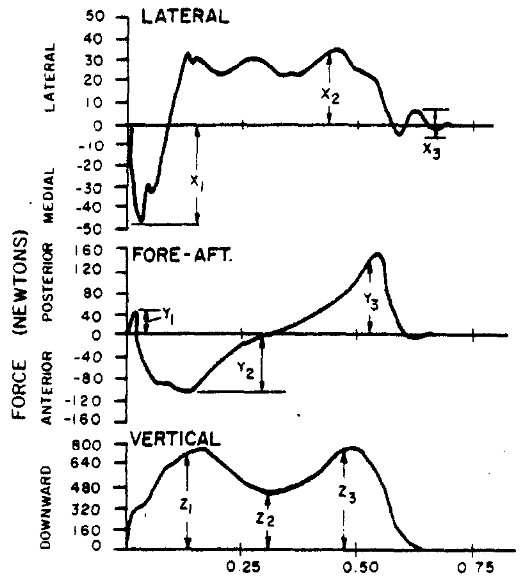

Fig. 4. An illustration of the waveforms depicting the three components of foot-ground reaction force.

maximum (*Y*3) amplitude posteriorly directed. The vertical component of force was characterized by the first maximum amplitude following heel strike (*Z*1), a minimum amplitude (*Z*2) following the first maximum and a second maximum amplitude (*Z*3) following the first minimum.

The 9 ground reaction force amplitudes described above were normalized to body weight and plotted in relation to forward walking speeds. The normalized force amplitude–velocity relationships obtained from all the normal subjects were combined (Fig. 5). The combined data for each of the 9 force amplitude–velocity relationships were approximated with linear, quadratic and cubic polynomial least square regressions. An analysis of the multiple correlation coefficients for the linear, quadratic and cubic polynomials indicated that the linear polynomial was adequate to describe each force amplitude and velocity relationship, a finding confirmed by inspection of the graphs in Fig. 5. The linear coefficient was found to be significant at $p > 0.9995$ for all amplitudes except *X*3 which was significant at $p > 0.995$.

The linear coefficient (β) of the normalized force magnitudes–velocity curve. the range of change in the force amplitude for slow to fast walking speeds and the percentage deviation (confidence interval $p = 0.95$) reported in Table 1 were used to quantitate the level of velocity dependence for each force amplitude. The minimum amplitude of the vertical force wave (*Z*2) was found to have the largest rate of change (β) with walking speed. Similarly *Z*1, *Z*3, *X*2, *X*3 and *X*1 amplitudes were considered to exhibit a meaningful velocity dependence. The *Y*1, *X*2, and *X*3 amplitudes did not show any meaningful changes with walking speed.

Gait observation of knee patients

Gait parameters for knee patients and normal subjects were compared by observing the entire velocity relationship. Data for a normal subject and a knee patient of the same stature were plotted on the same graph and compared (Fig. 1). There were several common areas where the gait patterns of knee patients differed from normal, although in some cases no differences could be observed. For example. patients with knee pathology were observed to have a shorter steplength and a higher cadence than normal subjects walking at the same average forward velocity. The data illustrated in Fig. 1 was measured on a patient with degenerative arthritis who was treated with a total knee replacement. The patient was observed at 3, 6 and 9 months postoperatively. Between 3 and 6 months postoperatively, an increase in steplength and a concurrent decrease in cadence was observed to achieve the same walking speed. Clinical improvement in the patient's knee function occurred at the same time. No change in steplength was observed between 6 and 9 months postoperatively, after clinical status had stabilized.

Table 1. Force amplitude–velocity curve fit data

Force amplitude	Linear coef. rate of change (β) with walking speed (sec/min)	Range of amplitudes* (slow gait)–(fast gait)	% deviation from linear fit confidence interval (P = 0.95)
*Z*1	0.257	0.75–1.80	±7.8
*Z*2	−0.330	1.0–0.20	±5.1
*Z*3	0.193	0.90–1.50	±12.4
*Y*1	0.018	0.01–0.16	±41.5
*Y*2	0.125	0.24–0.50	±7.5
*Y*3	0.118	0.04–0.38	±7.6
*X*1	0.058	0.02–0.25	±11.3
*X*2	0.013	0.01–0.15	±45.2
*X*3	0.008	0.01–0.00	±66.7

* Force amplitudes normalized to body weight.

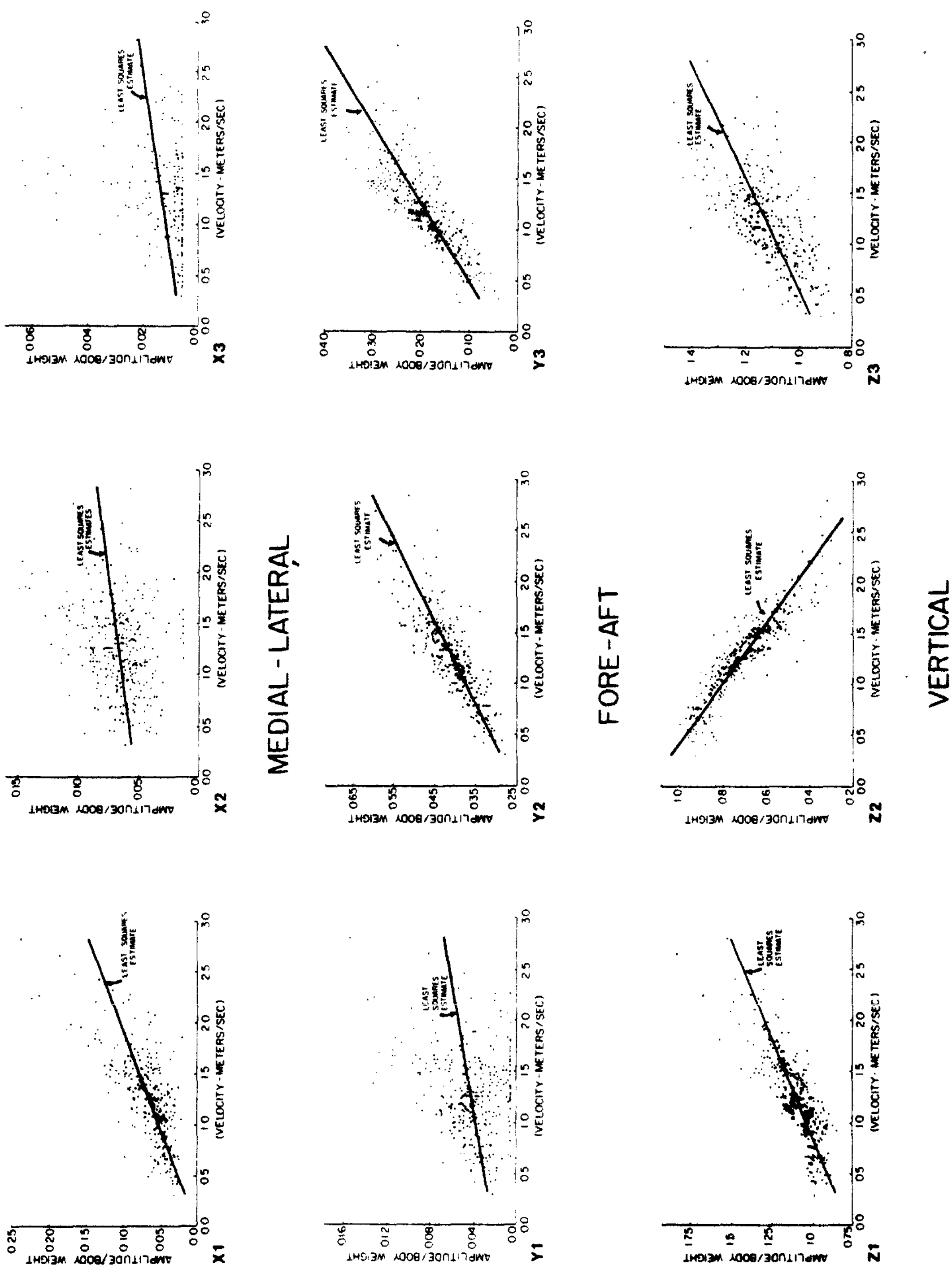

Fig. 5. The composite force amplitude and velocity relationships for the normal observations.

Table 2. A summary of the comparisons of temporal data for normal subjects and knee patients

	No. of observations	No. below normal	No. above normal	% below normal	% above normal
Velocity	34	34	0	100	—
Steplength	34	25	0	74	—
Cadence	34	0	25	—	74
Time of Support*	44	17	0	38	—
Time of Swing*	44	37	0	84	—

* Data from left and right sides were combined.

Knee patients were also observed to have shorter than normal time of swing and time of support. The time of swing and velocity relations shown in Fig. 2 were obtained from a normal subject and a knee patient of the same stature. The patient's time of swing–velocity relationship was below that of the normal, indicating a shorter swing time at any particular velocity. A difference could also be observed between the patient observations preoperatively and 6 months postoperatively after total knee replacement. At 6 months postoperatively, the patient's time of swing–velocity relationship shifted towards the normal with a concurrent improvement in her clinical condition.

A comparison of the support time velocity relationship for a normal subject and a patient of the same stature with rheumatoid arthritis and bilateral knee involvement is shown in Fig. 3. The time of support and velocity relationship for the knee patient was observed below the normal at 7 months preoperatively and immediately preoperatively. A marked shift from the normal could also be observed for time of support–velocity relationships between 7 months and immediately prior to surgery. This observation was consistent with a considerable worsening of the patient's clinical status and loss of knee function.

A total of 34 observations were made of patients with knee disabilities since 14 patients were observed twice and two were observed three times. For the purpose of this report, all patients observed were placed into a single category described as patients with knee disabilities.

The entire velocity relationship of each temporal parameter was compared to a normal for each patient (Table 2). This procedure was necessary because all patients walked at a slower than normal walking speed.

Time of swing was shorter than normal and was the most frequently occurring indicator (84%) of knee patient gait abnormalities. Steplength was observed shorter than normal in 74% of the observations while support time (including dual support time) was observed to be shorter in only 38% of the observations.

The relationship between ground-reaction force amplitudes and velocity for knee patients were also compared to normal in a similar manner to the temporal velocity relationship previously described. In general, the foot-ground reaction force amplitudes were not as sensitive an indicator of gait abnormalities as temporal measurements. A summary of the force comparison shown in Table 3 indicates that the medial force at heel strike ($X1$) was higher than normal in more than 50% of the observations. The fore-aft acceleration force ($Y3$) was below normal in 50% of the observations and the minimum amplitude of the vertical component ($Z2$) was below normal in 41% of the observations. The above observations were made on the basis of a comparison of the entire force amplitude–velocity relationship. Since many of the force components were shown to be velocity dependent, a valid comparison could only result from the entire force–velocity relationship.

DISCUSSION

It is reasonable to expect that gait patterns will vary with walking speed. People will normally walk at many different speeds. Therefore, observations are needed over a complete range of walking speeds to completely characterize a particular gait parameter. In addition, it was found that normal subjects walk at different speeds than patients with knee disabilities. Thus, when attempting to compare observations between normals and patients, it is essential to account for differences in walking speeds between the two groups.

It was shown that variations in temporal measurements with walking speed or ground reaction force

Table 3. A summary of the comparison of ground reaction force amplitudes for a normal subject and knee patients

Force amplitude	No. below normal (%)*	No. above normal (%)*
$Z1$	11 (32)	1 (3)
$Z2$	14 (41)	0 (0)
$Z3$	8 (23)	3 (9)
$Y1$	5 (15)	1 (3)
$Y2$	11 (32)	6 (18)
$Y3$	17 (50)	0 (0)
$X1$	0 (0)	18 (53)
$X2$	9 (26)	0 (0)
$X3$	0 (0)	9 (26)

* (34) Total observations.

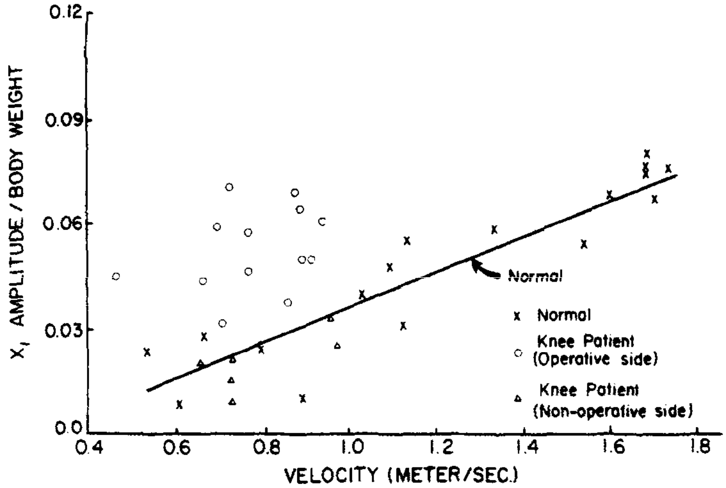

Fig. 6. A comparison of the force amplitude–velocity relationship for the medial force at heel strike for a normal subject and a patient treated with a total joint replacement.

measurements with walking speed can be described by simple mathematical relationships. For example, cadence and steplength were observed to vary linearly with walking speed while time of support and time of swing were observed to be inversely proportional to walking speed. Similarly, it was observed that force amplitudes $Z1$, $Z2$, $Z3$, $Y2$, $Y3$ and $X1$ vary linearly with velocity.

In addition, repeated observations on normal subjects indicated that gait measurements described by these simple velocity relationships are reproducible. Reproducibility of normal gait measurements was an important consideration since the observed differences in knee patients (Fig. 1) could be attributed to actual changes in gait patterns and not to variations in measurement techniques. Thus, it seems that rather simple measurements of temporal and ground reaction forces appear to be useful indicators of gait abnormalities when data is collected over a range of walking speeds.

Gait patterns of subjects with knee disabilities taken as a group (preop and postop) exhibited several common differences when compared to normals. For example, knee patients walk with a shorter steplength and a higher cadence than a normal subject walking at the same speed. Similarly, time of swing and time of support were shorter than normal for knee patients. Among temporal parameters, time of swing was the best indicator of gait abnormalities in knee patients. Repeated observations of knee patients indicated a shift in the steplength, swing time and support time relationship towards normal after knee replacement surgery. This finding was correlated with clinical and functional improvement of the knee joint.

Ground reaction forces were not as sensitive an indicator of gait abnormalities as temporal measurements with the exception of medial forces ($X1$ at heel strike) which were observed to be higher than normal (Fig. 6). At present, there is not sufficient data to determine the cause for this increased reaction force. However, the effects of this force should be considered since it could be damaging to a total knee replacement. The medial lateral force produces bending moments at the knee joints which could be conducive to early loosening of the prosthetic components.

Gait is an integrated pattern of movement. Changes in one parameter such as walking speed produce changes in the overall pattern of movement. To accurately characterize both normal and abnormal gait patterns, the interrelationship between various parameters should be considered. It was shown in this investigation that rather simple relationships (linear or quadratic) can be used to describe the relationship between various temporal parameters and velocity or ground reaction measurements and velocity. Gait measurements described in this manner were found to be reproducible for normal subjects and indicative of gait abnormalities in knee patients.

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