COMPARATIVE ANALYSIS OF THE KINEMATICS AND KINETICS OF FORWARD AND BACKWARD HUMAN LOCOMOTION

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Although common in occurrence one of the least studied modes of human motion is backward locomotion. Backward walking and jogging are currently being used as components of physical therapy for persons who have suffered trauma or submitted to surgery on the lower extremity or back as well as stroke patients. (Gray, 1985, Bates and McCaw, 1986; Kramer and Reid, 1981; Bates, Morrison, Hamill, 1984). Anecdotal reports of reduced noxious stress and beneficial proprioceptive stimulation have perpetuated the use of this form of physical therapy. Position specific sport training necessitates backward locomotion to engender efficient game performances. In numerous sport activities the defensive techniques employed entail retreating or "jockeying" maneuvers. Evasive offensive techniques likewise include backward travel. Some coaches and athletes are supplementing their conventional fitness training regimens with backwards running claiming enhanced hip extensor overloading with the resulting strength adaptation (Morton, 1985).

Cyclic loading of the foot during stance phase of gait must be understood in order to assess the overall effect of a locomotor style focally, segmentally and organismically. The need to quantify the pressures and temporal sequences operating at and between the individual foot segments during backward walking and jogging is, therefore, vital to understanding the entire array of lower extremity function. During forward locomotion the foot functions in two primary roles, as a loose force dissipating adaptor, and a rigid propulsive lever. Kinetic chain congruity of motion is predicted to a significant extent on segmental harmony of the anatomical components of the foot. How the foot segments interact during backward locomotion certainly effects the proximal kinetic chain components as well. Armstrong, Spyropoulos and Andres (1986) reported dissimilar vertical ground reaction force patterns when comparing forward and backward running. Thorstensson (1986) and Shuck (1986) reported uniquely divergent EMG patterns in backward walking as compared to forward walking.

The purpose of this study was to examine the amplitude and temporal characteristics of pressure at each of seven segments of the human foot during forward and backward locomotion in both walking and running.

Methods

Fourteen adult male volunteers with typical, non-extreme foot structures and without apparent or reported health or gait dysfunction were acclimated and habituated to a treadmill, after granting informed consent. Three treadmill training sessions of walking (1.34 m/s) and jogging 2.01 m/s) in forward and backwards directions were completed by each subject. A safety harness and handrails were utilized and the subjects mounted and dismounted the treadmill repeatedly to simulate the eventual testing procedure.

At the occasion of data collection the sensors of the Electrodynograph (EDG) were affixed to the planter aspect of the feet. Sensors L and M attached to the lateral and medial calcaneal tubercles. Sensors 1, 2, 5 attached to their respective metatarsal heads. Sensor X was affixed to the third metatarsal head and sensor H was attached to the hallucis. Each subject did eight trials for each of the four locomotor modes (Forward Walk FW; Backward Walk RW; Forward Jog FJ; Back Jog RJ). The first set of four trials of each mode were performed in random fashion followed by the second set of randomized trials in order to control for fatigue. The EDG Force Data Collector (FDC) 2A was used for walking trials and the 2S was used for jogging trials.

Once the subject had mounted the treadmill and was moving rhythmically on the treadmill the FDC was activated. Once the data were gathered the subject stopped from the treadmill and the data was transferred to a microcomputer for storage and subsequent treatment and printout. Each of the 32 trials for each subject was printed out and means of the three dependent variables for each sensor for each foot were calculated.

The statistical analysis was a univariate, repeated measures design with one grouping factor (foot-left and right) and two within factors (speed-walking and jogging and direction-forward and backward). The three dependent variables were duration percent of stance (D%), peak pressure (PP) and peaked at percent of stance (P%). Descriptive statistical analysis and the analysis of variance for each sensor were performed with the microcomputer program developed by Steinmetz, Romano and Patterson (1981).

Results and Discussion

Means and F values for the three dependent variables are presented in Figures 1-3 and Tables 1-3, respectively. The level of significance selected was $p < .01$.

TABLE 1. Summary of the Statistically Significant Main Effects and Interactions for Duration Percent of Stance by Sensor.

	Sensor F Values						
	L	M	5	X	2	1	H
Speed	130.88	75.30	13.35	133.12	199.87	233.45	176.60
Direction			8.74	11.74	9.17	9.47	
S x D	20.54	12.45		61.62	120.61	87.15	30.91
F x S x D			13.41				

TABLE 2. Summary of the Statistically Significant Main Effects and Interactions for Peak Pressure by Sensor.

	Sensor F Values						
	L	M	5	X	2	1	H
Foot		34.96	7.97				
Speed	89.95	72.43	50.03	139.67	80.13	143.02	46.98
Direction	49.34	42.99				45.93	8.18
S x D	98. 58	87.15		36.89	23.32	19.48	11.95

Table 2

TABLE 3. Summary of the Statistically Significant Main Effects and Interactions for Peaked at Percent of Stance by Sensor.

	Sensor F Values						
	L	M	5	X	2	1	H
Speed	79.21	51.58	8.74		11.05		
Direction	9216.76	3836.93	139.03	1373.62	1193.93	560.94	603.09
S x D	19.99	14.09	483.40	433.11	435.67	311.07	118.04

Foot Variability

None of the seven sensors demonstrated statistically significant differences between the feet for the dependent variables of duration percent of stance (D%) or peaked at percent of stance (P%). Differences were statistically significant for peak pressure (PP) at sensors M and 5 with the left medial calcaneus and the right fifth matatarsal head demonstrating greater pressures than their contralateral counterparts. Nakhla and King (1985) reported bilateral asymmetry in ground reaction forces for subjects tested on a treadmill. Evidently stabilization or centering on the treadmill is the causative factor. However, the bilateral asymmetry in this study was specific to peak pressures realized at two of fourteen sensors. For the dependent variables D% and P% as well as PP at the other twelve sensors the feet functioned consistently.

Directional Variability

All of the forefoot sensor sites demonstrated statistically significant differences for D% when forward and backward locomotion were compared. The calcaneus, hallucis and first metatarsal sensor sites demonstrated PP differences that were statistically significant. All sensor locations exhibited statistically significant differences on P%. Due to the considerable interactions between speed and direction a discussion of these differences will be dealt with below.

Speed Variability

All sensors evidenced statistically significant differences in the duration of sensor activation and the peak pressure when walking and jogging were compared. Walking and jogging expose the foot to quite different durations of exposure to the stress of pressure. Sensor sites L, M, 5 and 2 exhibited statistically significant differences on the dependent variable PP. A discussion of the implications of these results is provided in the next section.

Speed and Direction Interaction

It is the interaction between the speed and direction variables where some practical significance resides. For the sake of clarity the following sections are devoted to this interaction for each of the three dependent variables.

Duration Percent of Stance

The forefoot was on the ground longer during FW than during RW but during jogging the forefoot is on the ground longer during RJ than during FJ. The extreme of foot segment contact with the supporting surface were found in RW and RJ. In RW the lowest forefoot duration values were realized while the greatest rearfoot values were also realized. The percentage of stance phase duration were very high at the forefoot and the rearfoot values were very low in RJ. Increased duration of pressure, whether on the rearfoot in RW or on the forefoot in RJ means more compressive loading over time, which could be deleterious to the boney and soft tissues. Sensor 5 was the only sensor which did not demonstrate a statistically significant interaction between speed and direction. Regardless of the speed/direction combination the fifth matatarsal head experienced relatively long duration pressure application.

Peak Pressure

All sensor locations except sensor 5 demonstrated statistically significant interactions between speed and direction for peak pressure. The greatest rearfoot pressures were found in RW and FJ. The greatest forefoot pressures were found during RJ with the highest being recorded at the second metatarsal head. The lowest pressures were recorded at the lateral calcaneal tubercle during RJ. Hallucis pressure were quite similar for FJ and RJ. Lowest hallucis pressures were realized in RW.

Pressures exerted on the foot are to two origins, impact (passive and propulsive (active) loading. Pressure, whatever its genesis, will be managed effectively or it will be injurious. It is clearly evident from this study that backward walking and jogging result in more extreme pressure levels than the forward counterparts.

Peaked at Percent of Stance

All sensors demonstrated an interaction between speed and direction of travel for P%. The most remarkable comparative data is that of RW and RJ. Peaking of pressure in RW occurs in the forefoot between approximately 17% to 24% of stance. In RJ peaking in the forefoot occurs from approximately 34% to 55% of stance. In light of the force platform research of FGRF by Armstrong, Spyropoulos and Andres (1986) it can be concluded that the large forces recorded during FJ are propulsive in nature. Armstrong, et al., found a single peak in RJ associated with propulsion. Impact forces were considerably less than in FJ in their study. Early stance phase peaking of pressure in RW appears to contrast with this late peaking seen in RJ. It would seem that RW forefoot peak pressure events are associated with impact shock and, therefore, represent a different loading sequence than that seen in RJ.

TABLE 4. Rank Order of Duration Percent of Stance for Sensors by Locomotor Mode and Foot.

	Locomotor Mode							
	FW		RW		FJ		RJ	
	FOOT							
Rank Order	L	R	L	R	L	R	L	R
1	5	5	5	5	1	5	1	1
2	X	X	1	X	5	1	2	2
3	1	2	X	2	X	X	X	X
4	2	1	2	1	2	2	5	5
5	M	H	M	M	H	H	H	H
6	H	M	L	L	M	M	M	M
7	L	L	H	H	L	L	L	L

Foot Segment Variability

In FW, RW and FJ the fifth metatarsal head sensor was active for as great or greater a percentage of stance than the sensors at any other foot segment. In RJ metatarsal heads 1, 2 and 3 were ranked ahead of sensor 5 for D% and the values were much higher for these medially situated landmarks (See Table 4). This indicates that the forefoot experienced a larger pronatory event during RJ than was realized in the other locomotor modes. The ratio of pressures realized between sensors 1 and 5 are vastly greater in RJ than in any other locomotor mode. Though the patterns of pressure are similar, i.e., sensor 1 peak pressures always exceed those of sensor 5, the magnitude of difference is much greater in RJ (see Figure 2). Evidentially, while the forefoot is rocked more dramatically into pronation during RJ these first metatarsal pressures become very pronounced.

The sequence of pressures through the foot, as measured by the P%, showed further indication of a difference in foot function when the locomotor modes are compared. Figures 4A and 4B show these P% progressions. The pattern was distinctly different in RJ from FW and FJ. The progression of the peak forces in RJ are from sensor H to 2 to

1 then to X and 5. When reversed, disregarding the calcaneal sensors, the order is 5, X,1,2,H. In forward travel (and the left foot during RW) the order is 5, 1,X,2,H. The interpretation of this dissimilarity may be that a more medially-oriented forefoot is realized in RJ during the propulsive phase of gait when compared with the forward modes of locomotion. This is consistent with the previously mentioned observations in indicating a more pronounced forefoot pronation during RJ.

When the three previous observations are integrated it is apparent that RJ manifests a unique locomotor pattern. Foot posture, maximum and minimum peak forces and duration percent of contact during stance phase are radically different. It is concluded that the forefoot travels further into pronation before being reversed by what must be tremendous muscular effort. Thorstensson (1986) observed that anterior tibialis EMG activity demonstrated a burst of activity during the propulsive phase of stance during RW that resulted in a reverse torquing of the foot/ankle complex into plantar flexion. It is probable that in RJ the magnitude of this activity would be significantly greater to not only drive plantar flexion but also to actively supinate the foot from its extremely pronated position.

Of considerable importance is that the pronounced pronation in retrograde travel must have two effects on the tibialis anterior; generation of elastic energy and facilitation mediated by the myotatic stretch reflex. These two effects may have important implications for the rehabilitation of the neurologically impaired patient who requires an enhanced locomotor style to begin gait training.

It has been reported that prolonged RJ results in significant delayed muscle soreness (Gray, 1985). This may be accounted for by the eccentric control of not only the obvious calcaneal lowering but also the extreme pronation of the forefoot. Due to the oblique course of the triceps surae it functions eccentrically to lower the medial calcaneus under control. In light of the extreme pronation of the forefoot during RJ, and perhaps RW, it is a reasonable assumption that the gastrocsoleus complex decelerates pronation of the calcaneus and then actively returns the calcaneus to neutral under greater duress than in other locomotor modes.

The shock attenuation mediated by the triceps surae and the deep posterior compartment muscles certainly is a vital component to reduced stress at the knee but this aspect of RW and RJ was not included in this study. Intuitively, it is concluded that it is contraindicated to use RW or RJ in the acute or subacute stage of gastroceoleus injury or medial posterior tibial syndrome. However, in the chronic stage during which maturation and remodeling of tissue is occurring the eccentric loading, if moderated, can result in strengthening of the repairing structures.

The miniscule pressures realized at the heel during RJ means that persons suffering from calcaneal periostitis could substitute RJ for the more noxious FJ. The rapid peaking, high pressures exerted at the calcaneus in FJ results in great discomfort for the athlete with a heel bruise which leads to the avoidance of running or to the alteration of their gait. The latter can induce injury to other anatomical structures. By using RJ, fitness enhancing work-outs can continue while the periostitis is resolved.

The efficacy of substituting RW or RJ for more conventionally prescribed alternatives to FW or FJ is based on the benefit of continued weight bearing and rhythmic oscillation of the extremities. Historically, swimming, rowing and bicycle riding have been advocated for persons with heel, ankle, knee, hip and low back injuries. While sound in the intent of the recommendation of continued activity during convalescence, these alternatives lack the inherent specificity that retrograde locomotion affords. The proprioceptive benefit of moving through similar ranges of motion as that experienced during forward travel while resisting gravity's influence is extraordinary. As long as contraindicated applications of RW and RJ are avoided and rationality is exercised as to the duration and intensity of their use, the medical description of the "retro syndrome" can be eluded.

The consensus regarding the leading etiological factor in the production of chronic lower extremity injury is that of training errors, i.e., "too much, too soon" (James, 1985). This certainly pertains to the inclusion of RW and RJ into a fitness regimen. A gradual exposure to backward travel is necessary in order to avoid chronic injury. It seems rational to consider RW and RJ as adjunctive to a fitness program as opposed to an exclusive means by which to promote and maintain fitness. The very large pressures, the long duration forefoot exposure to pressure and the extremes of motion found in RJ require judicious acclimatization to and use of this method of fitness training.

Conclusions

The study of the effect on pressure and temporal parameters by two directional travel, at two different speeds, yielded a great deal of information. The results indicate that the feet perform symmetrically in all of its segments during treadmill travel with the exceptions of the fifth metatarsals and the medial calcanei which recorded asymetrical peak pressures.

Backward locomotion results in very different quantities, distribution and duration of application of the pressures that are exerted onto or generated by the foot. Extremes of pressure duration, minimum and maximum were realized in backward travel. Extremely large pressures were found at the forefoot in backward jogging while extremely low pressures occurred at the rearfoot. Forefoot and rearfoot pressures during backward walking were less or comparable with those recorded in forward walking.

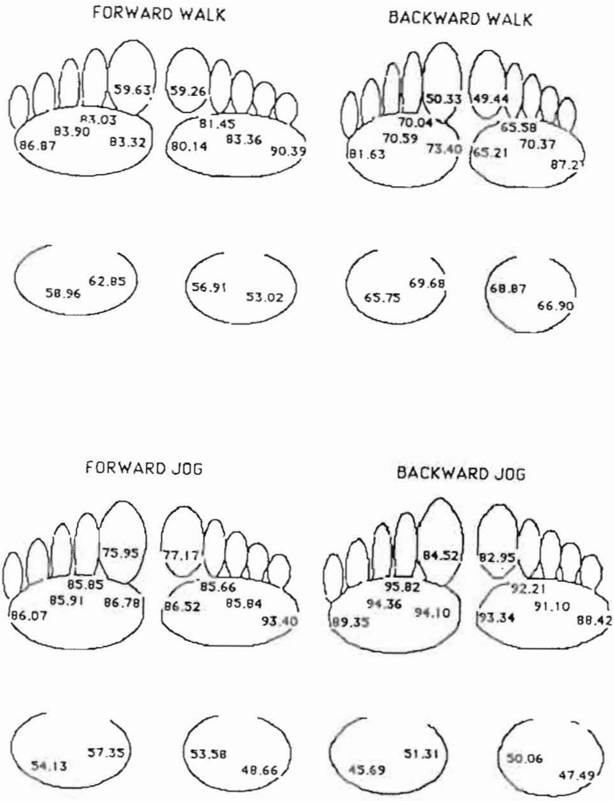

FIGURE 1. Duration percent of stance by locomotor mode.

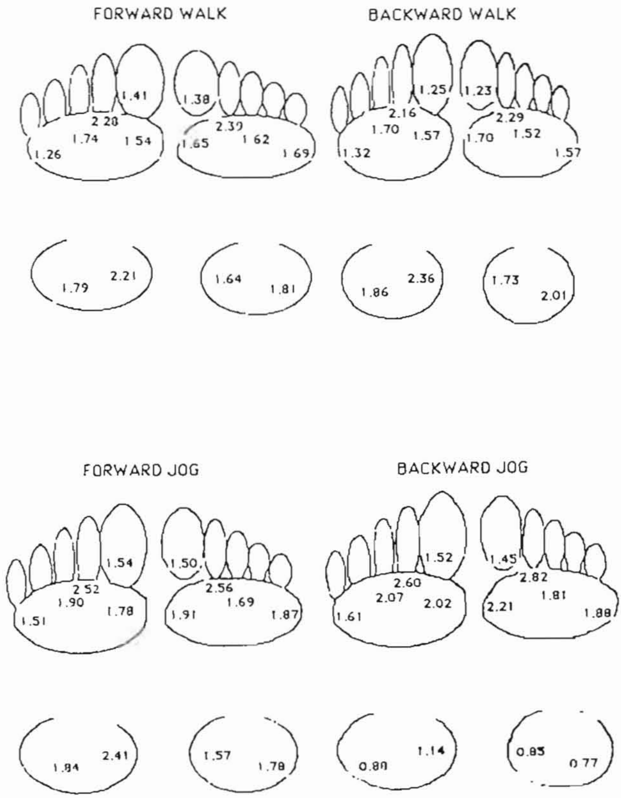

FIGURE 2. Peak pressure by locomotor mode.

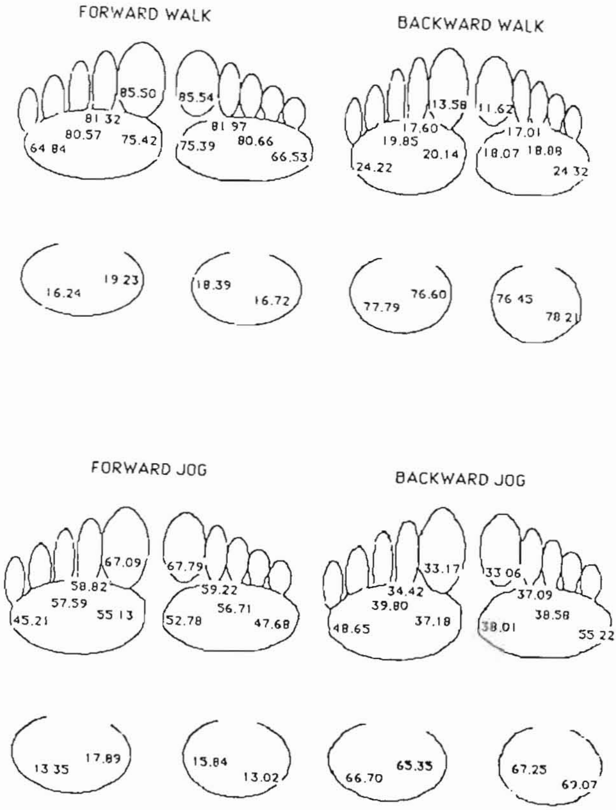

FIGURE 3. Peaked at percent of stance by locomotor mode.

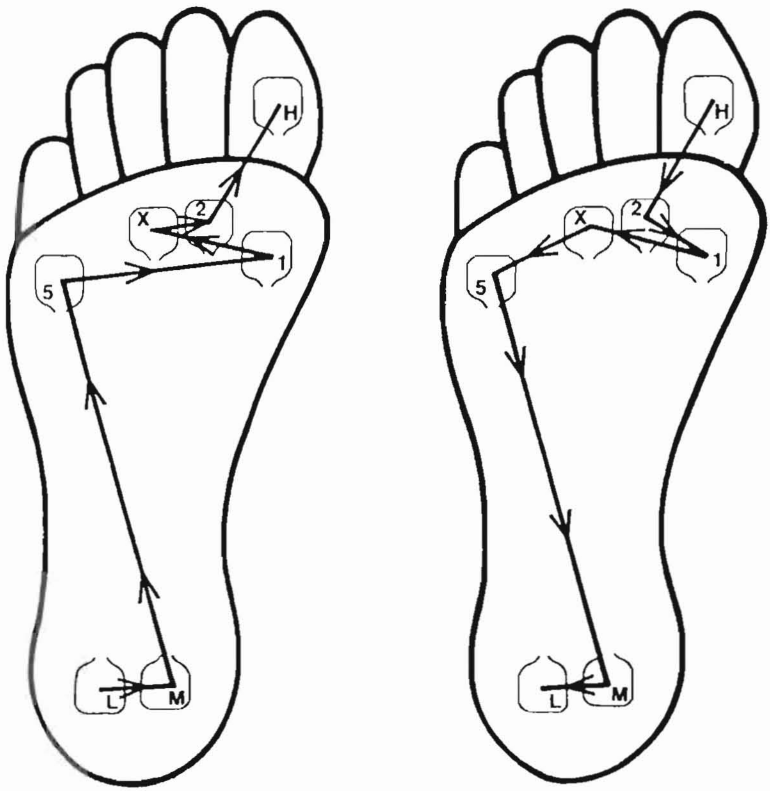

FIG. 4A
Sequence of pressures during FW & FJ.

FIG. 4B
Sequence of pressures during RJ.

FIGURE 4 A & B. Sequence of peaking pressures for the left foot.

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