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OVERALL PRINCIPLE OF LOWER LIMB SUPPORT DURING STANCE PHASE OF GAIT*

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Abstract – The basic function of the lower limb during stance is to resist collapse and to extend sufficiently to achieve the required push-off. Collapse of the lower limb requires a flexion at all three joints (knee, ankle and hip), thus support of the body requires net extensor activity at these joints. A new support moment, M_s, is defined as the algebraic sum of the extensor moments at the three joints, and for 24 subjects, nine patient and three jogging trials M_s was calculated and found to be positive (net extension) over the stance period. Normalizing the peak amplitude of M_s to 100% and averaging these curves over 100% of stance revealed a significant basic pattern. The ensemble average of 12 subjects walking at their natural cadence was very similar to the ensemble average of a mixed group of 24 subjects (walking at fast, natural and slow cadences) and 9 patients. Examination of individual subject and patient joint moment histories revealed considerable variability at the knee and hip in spite of consistent M_s patterns. For example, one knee replacement patient had a moderate knee flexion for the entire stance period but compensated and prevented knee collapse by large hip extension during that time. The three joggers also showed a consistent M_s pattern in the presence of individual variations at the knee and hip; however, the shape of M_s curve had a single peak compared with a double peak for the walking trials.

INTRODUCTION

One of the most valuable biomechanical variables to have for the assessment of any human movement is the time history of the moments of force at each joint. These kinetic patterns give valuable insight into the net effect of all agonist and antagonist muscle activity, and thus represent an integration of all the neural control acting at each joint. The purpose of this paper is to identify and validate a single control pattern that appears to be present in all types of gait: normal walking, jogging and many types of pathological gait. The principle of lower limb support is simple: the algebraic summation of all extensor moments at the ankle, knee and hip must be positive (and sufficiently so) during the stance period. Such a principle can now account for apparently anamolous patterns observed at individual joints in both normal and pathological gait: i.e., the presence of complete or dominant knee flexor activity during the entire stance period, yet no apparent knee angle history to indicate collapse.

REVIEW LITERATURE

A detailed look at the papers that have reported joint moment histories of the lower limbs during walking (Elftman, 1939; Bresler and Frankel, 1950; Paul, 1966; Morrison, 1968 and 1970; Paul, 1971; Pedotti, 1977; Johnson and Waugh, 1979) is quite revealing:

1. Only 18 case histories of moments at all three joints have been reported, with seven additional records of knee moments only.
2. Only the ankle joint has a consistently recognizeable pattern: a small dorsiflexion moment followed by a strong plantarflexor moment.
3. The hip has a less consistent pattern, but it is usually extensor followed by flexor.
4. The pattern at the knee is quite inconsistent and quite unpredictable.

A review of the same patterns in 30 subjects and 9 patients assessed in our Laboratory over the past three years reinforced the above observations. More details of the patterns of joint moments reported by the above authors is presented in Table 1. Summarized are the peaks of flexor (f) and extensor (e) moments at each joint; all units have been converted from their original units to N.m. It is worth commenting on the inconsistent and sometimes anamolous knee moment patterns. For three of the four subjects reported by Bresler and Frankel there was negligible extensor activity during weight acceptance; the dominant activity was actually flexor. Pedotti also reported one subject with flexor activity during the entire stance phase. Morrison's three subjects in his 1970 report had very little knee activity of any sort during stance. Yet, in all cases there was nothing abnormal reported about their gait patterns (such as excessive knee flexion). In fact, with the forces of gravity acting across a flexed knee in the normal range (15°–20°) at mid stance one wonders why questions were not raised as to why they did not collapse?

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Table 1. Peaks of muscle moments – flexion (f), extension (e)

	Hip (N. m)		Knee (N. m)		Ankle (N. m)	
	Wt. accept.	Push off	Wt. accept.	Push off	Wt. accept.	Push off
Elftman (1939)	30(e)	90(f)	40(e)	50(e)	10(f)	100(e)
Bresler & Frankel (1950)	88(e)	60(f)	48(e) + 40(f)	15(e) + 37(f)	28(f)	98(e)
	35(e)	100(f)	16(e) + 75(f)	48(e) + 35(f)	27(f)	115(e)
	32(e)	75(f)	5(e) + 42(f)	50(e) + 15(f)	36(f)	122(e)
	95(e)	170(f)	5(e) + 85(f)	17(e) + 85(f)	20(f)	140(e)
Paul (1966)			100(e)	25(f)		
Morrison (1968)			48(e) + 35(f)	28(e)		
Morrison (1970)			2(f)	7(e) + 2(f)		
			1(f) + 5(e)	10(e) + 2(f)		
			7(e)	17(e)		
Morrison via Paul (1971) (10 subjects)	75(e)	50(f)	25(f) + 30(e)	25(f)	15(f)	100(e)
Pedotti (1977)	75(e)	30(f)	30(f)	65(f)	15(f)	150(e)
	75(e)	50(f)	40(f) + 40(e)	50(f) + 25(e)	10(f)	160(e)
	100(e)	70(f)	50(f) + 80(e)	10(f)	15(f) + 85(e)	100(e)
Johnson & Waugh (1979)			110(f)	65(e)		

LOWER LIMB SUPPORT

Prevention of collapse during weight bearing can be accomplished by collaboration of muscles at all three joints of the lower limb. To collapse the knee during weight bearing there must also be a simultaneous collapse at the hip and ankle. Thus a net moment at any of these three joints which prevents collapse will contribute to lower limb support. In Fig. 1 we see these muscle moments at each joint (with the convention of positive counter clockwise moments). The net supporting moment, Ms, during stance is defined as $Ms = Mk - Ma - Mh$, where Mk, Ma and Mh are the moments at the knee, ankle and hip, respectively. A few comments should be made concerning the roles of Ma and Mh. With the foot on the ground, especially during flat foot, Ma is negative when plantarflexors are dominant. Such muscle tension acts to decelerate the forward rotation of the leg and prevent knee flexion. When Mh is negative the hip is trying to extend, thus rotating the thigh in such a direction as to prevent knee flexion. Thus when any of these muscle moments are extensor they will contribute a positive component to Ms. As long as Ms is positive there is a net tendency to support the lower limb and prevent its collapse. It also means that when one joint opposes or does not contribute to lower limb support one or both of the other joints will compensate for the non-contributing joints. This theory was tested using data from normal walking, pathological gait and joggers.

METHODOLOGY

Coordinate data were obtained from all subjects and patients walking at a variety of cadences in the Gait Laboratory in the Department of Kinesiology at the University of Waterloo. Each subject had reflective markers attached on the following anatomical landmarks: toe, metatatsophalangeal (*m–p*) joint, heel, ankle (lateral malleclus), lateral head of fibula, lateral epicondyle of femur, greater trochanter, illiac crest, and mid-trunk region. Each subject wore his own footwear, and walked on a raised walkway while a tracking cart, carrying a TV and cine camera (50 frames/sec) was guided on a track at a distance of 4 meters. Background markers on the wall beside the walkway gave a "yardstick" reference so that body coordinates could be properly scaled, and obtained as absolute coordinates (Winter *et al.*, 1972). Simul-

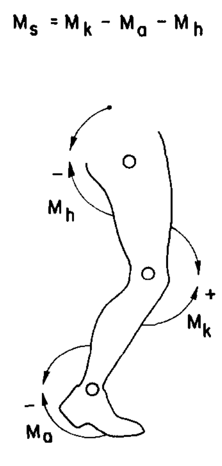

Fig. 1. Moments of force at the ankle, knee and hip during stance, with extensor moments shown. Convention has counter-clockwise moment acting at proximal end of any segment as being positive. Ms is the total extensor moment acting on the lower limb segments.

taneously, force plate data were recorded, along with a 50 Hz synchronizing pulse obtained from the cine camera. The force plate data yielded the vertical and fore-aft shear ground reaction forces, and when combined with the cine data the centre of pressure of these forces under the foot was obtained.

Coordinates of the body and background markers were extracted from cine film using a Numonics Digitizer interfaced with a NOVA 1200 computer. Raw coordinate data were scaled, then corrected for parallax error between the plane of progression of the subject and the plane of the background. Using the background markers as a spatial reference the limb markers absolute coordinates were calculated, and then transferred to an IBM 370 computer for kinematic processing. The "noise" in this coordinate data, mainly due to the digitizing process, has been calculated to have an r.m.s. error of 2 mm. Prior to link segment kinematic analyses the coordinates were digitally filtered (Winter, *et al.*, 1974) using a 4th order, zero lag low-pass Butterworth filter cutting off at 5 Hz. Validation for the filtering and finite difference calculation of velocities and accelerations is supported by the study by Pezzack and colleagues (1977). For each subject anthropometric data were obtained using tables provided by Dempster, based on the subject's height and weight.

A standard link segment kinetic program (Bresler and Frankel, 1950) calculated the vertical and horizontal reaction forces plus net joint moments at the ankle, knee and hip for one complete stride, commencing with heel contact. Then *Ms* was calculated and stored with *Ma*, *Mk* and *Mh* for future processing and plotting. It should be noted that the foot was modelled assuming a rigid segment between the ankle and the *m-p* joints. The toe marker was not used because of flexion and extension of the *m-p* joints, especially during late push-off and early swing.

RESULTS AND DISCUSSION

Some example patterns of *Ma*, *Mk* and *Mh* are presented to illustrate the degree of variability seen at each joint along with the resultant *Ms*. Figures 2 and 3 show the joint moment histories for two normal subjects, chosen to indicate the wide range of patterns, especially in *Mk* and *Mh*, yet with similar patterns of *Ms*. Figure 2 is the analysis of a male athlete with a fairly lively "bouncy" gait. The major contributor to support during weight acceptance (0–250 ms) were the hip muscles which had pronounced extensor activity. The knee was actually in slight flexion not only for weight acceptance but for most of stance. The ankle plantarflexor moment, was quite normal and also stabilized the lower leg. During mid stance and push-off the ankle was the only major contributor to support as the hip went into flexion. Figure 3 reveals somewhat different patterns in a female subject. The ankle moment history is quite typical: a small dorsiflexor moment after heel contact to lower the foot to the ground, followed by major plantarflexor activity. The knee had distinct extensor activity during weight

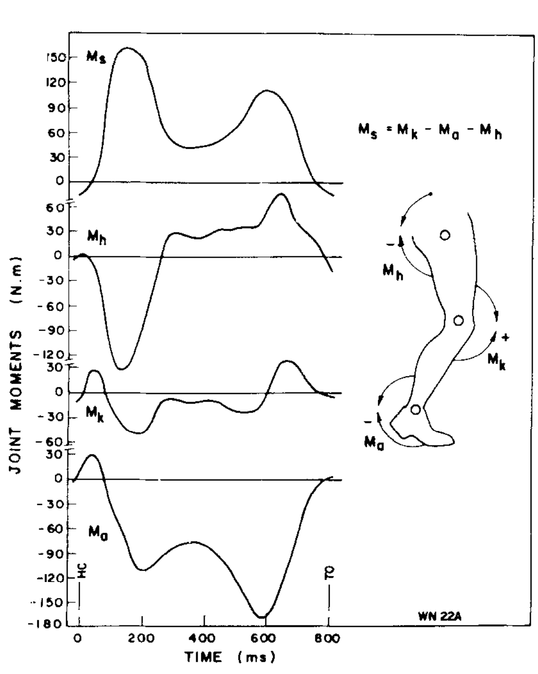

Fig. 2. Joint moment patterns for normal walking of a young male athlete. See text for details.

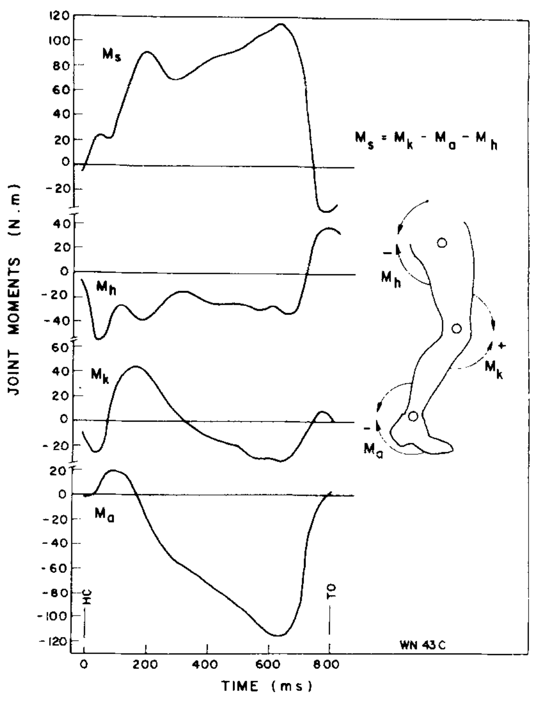

Fig. 3. Joint moment patterns for a young female walking at natural cadence. See text for details.

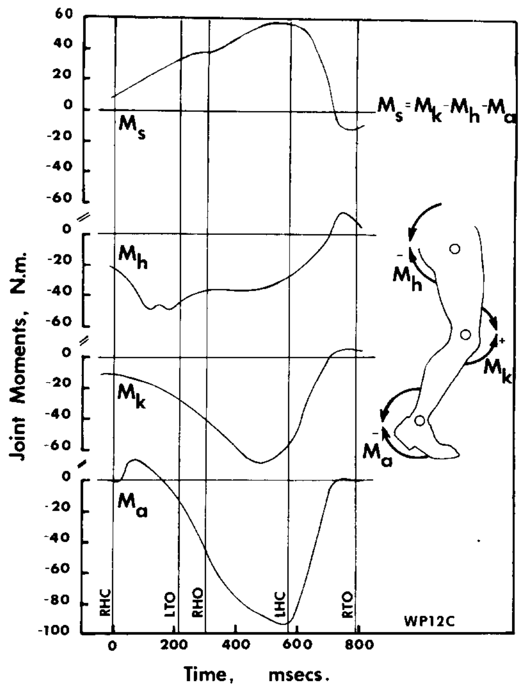

Fig. 4. Joint moment patterns for a 73 year old knee replacement patient. See text for discussion.

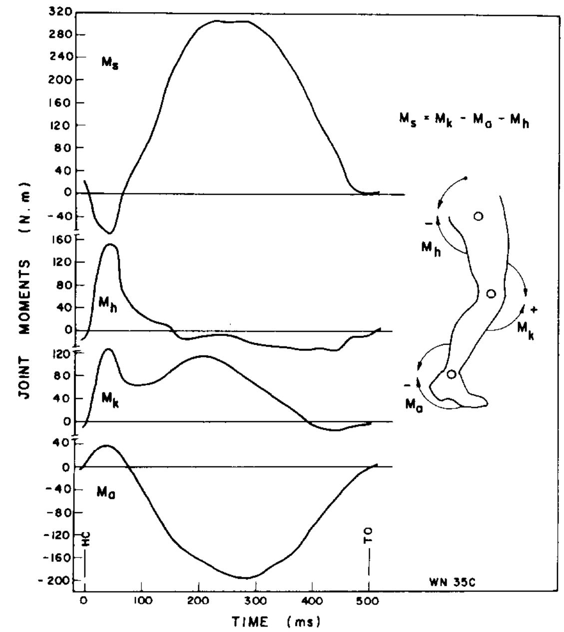

Fig. 5. Joint moment patterns for a young male jogging at a slow speed. See text for discussion.

acceptance and was reinforced by the hip extensor moment. Until about 300 ms all three moments contributed to limb support. During mid stance and push-off the knee went into flexion, the ankle and hip compensated to maintain lower limb support.

The results from the assessment of a knee replacement patient are quite revealing in the apparently anamolous knee moment history. This patient, a 73 year old female, has suffered for 10 years from osteoarthritis prior to knee surgery. The post surgical assessment (Fig. 4) shows her knee moment to be negative (flexion) during the total stance period. In spite of this *Ms* is still significantly positive, and this can be traced directly to a large extensor (negative) hip moment plus a greater than normal plantarflexor (negative) ankle moment. Here, both the hip and ankle have more than compensated for the knee joint. The clinical significance of these findings are beyond the scope of this present paper; however, such a case study provides dramatic evidence to support the basic principle of lower limb support.

One of the three joggers assessed had joint moments as presented in Fig. 5. This male jogger achieved lower limb support with a normal ankle moment pattern plus strong knee extensor activity. The hip had major flexor activity during weight acceptance, sufficiently large to override the knee extensors, and result in a small negative *Ms*. The effect of this net "collapsing" moment was minimal because it lasted for only 60 ms, and the lower limb responded with a very rapid rise of *Ms* to over 300 N.m. This short duration negative *Ms* was present in the other two joggers, and is likely part of the shock absorbing mechanism as the lower limb protects its own joints and the vital organs of the upper body.

Average curves of *Ms* for selected groups of subjects were determined from their normalized curves: with stance period = 100% and maximum *Ms* set at 100%. These curves were averaged over stance for similar groups of subjects and gaits. Figure 6 shows the average of *Ms* for the three joggers, the vertical bars represent one standard deviation either side of the mean. Figure 7 is the average of 12 normal subjects walking at their comfortable cadences, and Fig. 8 has a mixed group of thirty-three subjects and patients (hemiplegic, amputees, and knee replacement) walking

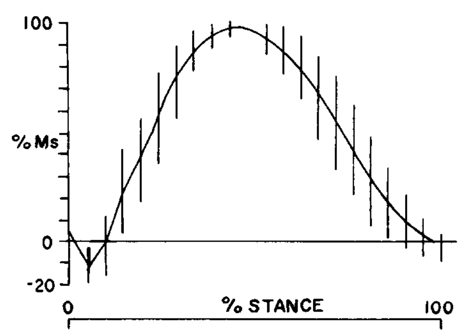

Fig. 6. Total support moment, *Ms*, averaged for 3 joggers. Peak *Ms* was set to 100% and stance period was set to 100% before averaging. Vertical bars represent one standard deviation from the mean.

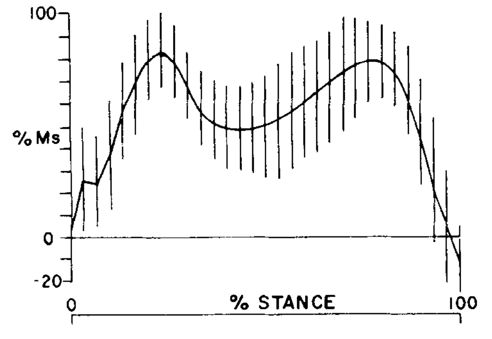

Fig. 7. Support moment, *Ms*, for 12 normals walking at comfortable cadence. Basic pattern shows a peak of support during weight acceptance followed by a second peak during late push-off.

at a wide range of cadences. The pattern of *Ms* for the 3 joggers shows relatively small deviation over the 100% stance period. Except for the initial weight acceptance period when *Ms* is negative this curve has a striking resemblance to the ground reaction force curve. This is probably not too surprising since *Ms* is the algebraic sum of the three extensor moments, and, as such, represents the net tendency of the lower limb to push away from the ground.

Figure 7, for normal walking also shows a relatively small deviation about its mean. The shape of this *Ms* curve, with its characteristic double peaks is quite similar to the ground reaction curve. Finally, Fig. 8, the average curve for the widely varied subject and patient population shows the existence of the basic *Ms* pattern which is present in normal and pathological gait. It is quite surprising that the curve has so little variability considering the wide variety of normal cadences and pathologies represented.

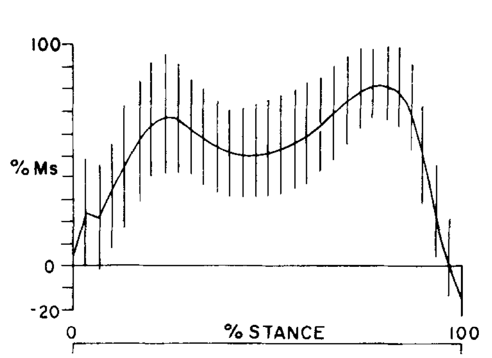

Fig. 8. *Ms* for a total of 33 normals and patients walking at a variety of cadences. Net pattern for this variable group is quite similar to that seen for the normal group (Fig. 7).

CONCLUSIONS

Based on the similarity in the patterns of *Ms* across a variety of subjects and patients, and the variability of the moments of force at the individual joints the following conclusions can be made:

1. Support during stance is achieved by a net extensor pattern of moments at the ankle, knee and hip joints.
2. Kinetic assessments of gait should examine the total limb rather than focus on any single joint. In fact, it is now evident that the analysis of any single joint can lead to an erroneous diagnosis.
3. The ability of one joint to compensate for the lack of support at another joint is now evident, and such mechanisms are extremely important in the management of a physically handicapped patient.
4. As to the basic neurological mechanisms, the overall patterns demonstrated here may assist neurophysiologists in interpreting EMG patterns, especially the individual and stride-to-stride variability.

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