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The Human Walking: A Biomechanical Analysis

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SUMMARY

A study of normal walking requires an understanding of both the movement of limbs and their control involved. This is equally true in appreciating the problems of pathological gait. The walking cycle is described in terms of the significant event which occur during both the stance and swing phases. The basic principles underlying the analysis of limb movements and their possible control are described. The muscle actions required to move and resist turning actions and joints during walking are briefed electromyographically.

INTRODUCTION

Walking is one of the most common of all human activities. It appears to be simple but is controlled by complicated and meticulous co-ordination between various elements. Like most other functions it varies from one person to another. Bernstein[1] argued that an individual's ability to function effectively within his environment is largely dependent upon walking man's most commonly performed motor act. Hughes & Jacobs[2] suggested that normal human walking is the rather grand term given to the description of walking of individuals who fall within the range considered as "normal". It is a highly individual and variable activity influenced by age, sex, body build, physical condition, temperament, fatigue and many other less obvious factors. Despite the enormous variability there are characteristic actions which are common to all forms of normal walking e.g., phases of the step cycle, angular displacements, muscular activity in different muscles of the limb and forces acting at the limb joints.

Interest in the study of muscular control of walking was sparked off by the early works of the Weber brothers[3] who claimed that during the swing phase of walking, muscular control was not necessary and the motion of the leg occurred much like a simple pendulum. Further contributions to the study of human walking were made by Marey[4] in France, Braune & Fischer[5] in Germany and Bernstein[6] in Russia. Elftman[7] studied the distribution of pressure under the human foot, the function of arms in walking, the rotation of the body and the functions of muscles in locomotion.

With advancements in electronic technology, new methods have enabled quantification of variations in walking from subject to subject. Several approaches and numerous methods have been used to obtain temporal kinematic and kinetic information relative to normal walking and to walking patterns associated with different pathological processes. Investigators have used the following techniques either separately or in combination to study walking: Electromyography[8,9], Electrogoniometry[10], Force-Plates[11], Cinematography[12], Interrupted Light Photography[13], Accelerometry[14], and Foot-Switches[9,10]. Numerous mathematical models have been described in the literature for analysis of body movements using rigid body idealization with active controls at different joints[15]. Townsend & Seireg[16] developed a computer based procedure for the trajectory synthesis and control of bipedal locomotion for optimum stability and energy expenditure. The problem of determining the load sharing between the different muscles in order to maintain a particular posture has been investigated by Seireg & Arvikar17.

PHASES OF THE WALKING CYCLE

Hughes & Jacobs[2] described a visual and simple display of the events in the walking cycle i.e. the period which starts the instant one foot contacts the ground (Fig.1). The walking cycle is composed of two separate phases - the "Swing-phase", when the foot and leg are swinging forward to be placed in front of the body and the "Stance-phase" when the foot is in contact with the ground, till the beginning of the next cycle. The stance phase accounts for about 60% of the cycle at normal

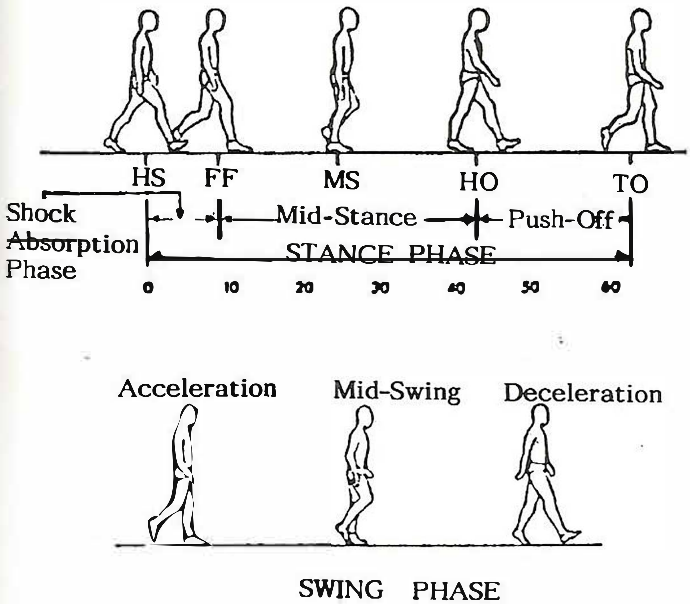

Fig.1: **The walking cycle showing events in stance and swing phase. HS = Heal Strike, FF = Flat foot, MS = Mid Stance, HO = Heal Off,**

walking speed, reducing as the walking speed is increased. The swing phase is sub-divided into three events. Acceleration, which is the period of acceleration of the foot in space(after toe-off), Mid-swing when both ankles are in opposition and coinciding with Mid-stance on the other foot and Deceleration, when the foot is being slowed down preparatory to placing on the ground (heel-strike) to begin another phase. The stance phase is itself subdivided into a number of events - Heel-strike when the heel contacts the floor, Flat-foot as the sole of the foot comes into contact with the ground, Mid-stance when both ankles are in opposition, Heel-off when the heel leaves the ground and ending with Toe-off when the foot loses ground contact. The period between Heel-off and Toe-off is known as push-off, when the ankle is actively plantar flexed. Double support periods occur when both foot are in contact with the ground at the same time. There are two such periods in every walking cycle, between Heel-off and Toe-off on one side and Heel-strike and Flat-foot on the other. The faster the speed of walking the less time is spent in double support. Indeed in athletic terms the definition of walking is that double support phase is maintained otherwise the subject is running and would be disqualified for competitive walking.

A walking cycle which consists of a stance and followed by a swing phase is generally described as a "Stride". "Pace" or "Cadance" is the number of strides taken in one minute and is reciprocally related to the duration of walking cycle. A "Step " is usually defined as the heel contact of one leg to the heel contact of the opposite leg[18].

"FLEXION" AND "EXTENSION" MOVEMENTS OF THE LIMB

Most studies of the neurophysiology of locomotion have been done on the cat. Originally the muscle activity during the cat's step cycle was divided into two phases, FLEXOR & EXTENSOR1[9,20] (Fig.2). Phillipson's21

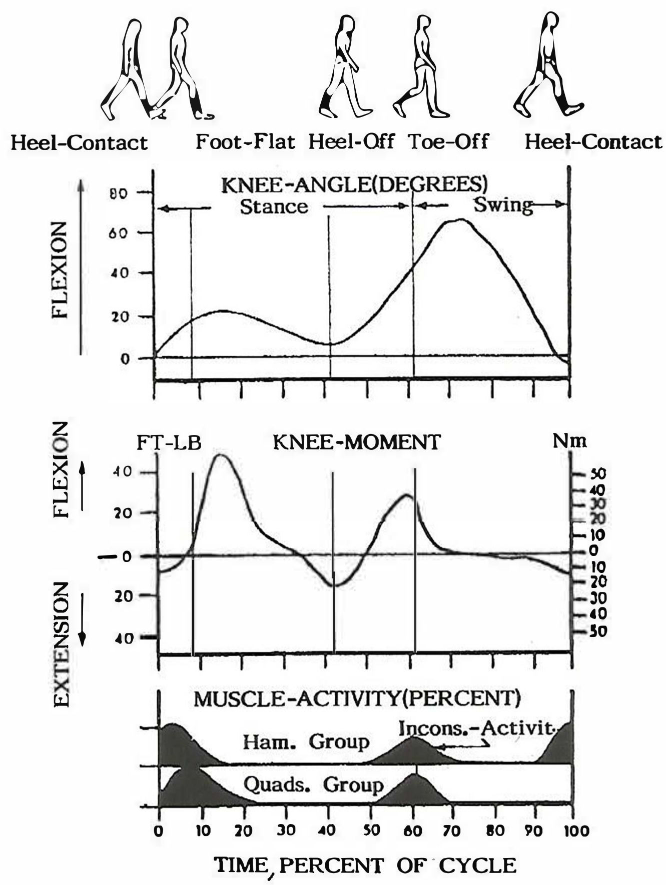

Fig. 2: **(Above) Variation with time of angle and moment at the knee joint. (Below) Phasic EMG pattern of Hamstringand Quadriceps group of muscles during normal walking (Adopted and modified from Hughes & Jacobs, 1969).**

characterization of the step cycle included a flexor (F) phase during early swing and an extensor phase (E)beginning in late-swing (E1) and lasting the entirety of stance (E2 & E3) The F phase was presumed to be associated with flexor muscle activity and E phase with extensor muscle activity[22]. A significant consequence of this biphasic nature of stepping is the concept that extensor activity during swing an extensor activity during stance are continuous and together compromise a single extensor phase. The purpose of extensor activity during swing phase is to stiffen the muscle in preparation for the load that the muscles bear during stance. Such preliminary stiffening is necessary because the time lag between sensory stimuli initiated at foot touch down and the reflex extensor response is too great to be immediately useful[23]. Extensor activity during the swing phase is not generally regarded as a requirement for knee and ankle joint. This is reasonable because hip flexor activity applies a torque to the limb the net effect of which is to permit extension at the knee and ankle when knee and ankle flexors turn off. Thus, in the cat much of the kinetic energy of knee and ankle extension could be derived from contraction of the hip flexor muscle.

Other investigators have noted that limb movements and limb muscle activities follow a triphasic pattern during purposeful behavior in vertebrates[24]. In all cases the three phases correspond to a propulsive phase, a phase immediately following propulsion in which the limb is braked, and a phase during which the limb is prepared in some fashion for the next propulsive phase. In the case of walking it has long been noted21 that the propulsive phase (i.e. stance) can be divided into two periods, the period in which weight is borne (E2) and the period in which the limb extends and pushes the body (E3). However, these two phases are dis-tinguishable only in behavioural and not in electrophysiological observations. All extensor muscles studied seem to be active at some level throughout E2 & E3.It is also possible that load bearing and propulsion are both occurring during both E2 and E3. On this level of observations of only time of muscle activities the step cycle has been previously regarded as being essentially biphasic i. e. Flexor and Extensor

MYO-ELECTRIC ACTIVITY OF THE LOWER LIMB DURING WALKING

The lower limb has assumed primary responsibility for human locomotion to allow man to move in a civilized world fashioned by his emancipated hands. It is fortunate for us, as suggested by Elftman[25] that this movement takes place in a gravitational field and can be controlled by muscles under central control and responsible to feed back from peripheral receptors. The movement of the leg in walking are caused by muscular activity. It has been noted that walking elicits very slight EMG activity in leg muscles compared to voluntary free movements[26]. Cappozo et al[27] reported that walking involves a series of co-ordinated movements of the body segments implying an interplay of muscular forces and external forces.

Several studies have been conducted on muscular activity of lower limb during walking. Much useful information regarding the function of the muscles and the phasic relationship of the activity has been obtained by the development and use of electromyography. There have been extensive studies of the electromygraphic signals from all important muscles during the walking. Comprehensive data can be found in studies by the University of California Berkley, Report[8], Houtz & Fischer[28], and Battye & Joseph[29]. The Report paper shows data from[28] muscles in each of six subjects in six locomotion activities (Fig.3). Battye & Joseph[29] have performed statistical analysis of the EMG data for a wider range of subjects but for a restricted number of muscles in level walking only. Such studies provide information about the pattern of muscles participation and differences in activity patterns during different physiological activities. Such differences in activity were mainly in the muscles responsible for the particular movement of the body. Milner et al[30]. Studied variations in muscular activity with speed and with different pacing constraints. These results indicate clearly that there is a strong dependence in each instance. They also reported that electromyography provides a measure of muscular energy expenditure. Boccardi et al[31]. suggested that muscular activity of normal subjects fits well with the articular dynamics; whenever the ground reaction produces a flexor or extensor moment at the joint the muscles providing an opposite moment at the same joint are active. The same muscles are silent when their activity is not required.

FACTORS AFFECTING NORMAL WALKING PATTERNS

Normal walking in man can be affected in any one of the following pathological states as reported by Yablon[32], shortened extremity, contracture, loss of supporting structure, pain and paralysis. Each of these states produces a characteristic alteration which can be observed and recorded by noting the movements of the pelvis and trunk and the position of the joints of the lower extremity. It has been reported by many investigators that a number of external constraints

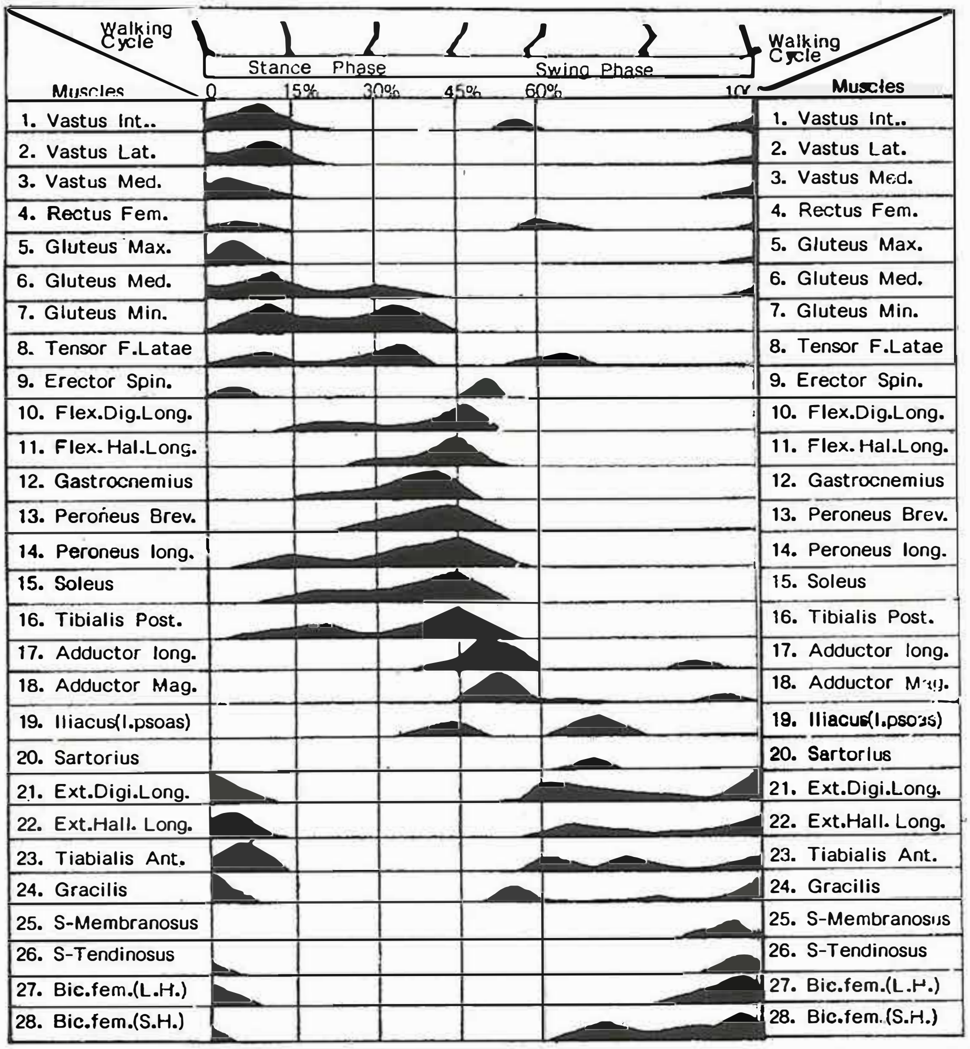

Fig.3: **Phasic activity of muscles of the leg obtained from electromyography records using needle electrodes. (Adopted from University of California "Report" 1953).**

during walking can also affect the current muscle activity and the pattern of the step cycle. Such constraints include presence of extra-load on the body[33] going up and down stairs[34], wearing of high heels[35] running[30], hopping or landing from a fall[36] and resistance of external forces[37] changes in the gait pattern with age have been reported by Beck et al[38]. They concluded that increase in height was the major factor in determining the changes in time and distance measurements with age

CENTRAL AND PERIPHERAL CONTROL OF WALKING

A number of advanced experimental approaches and intensive studies have proved in many non-mammalian vertebrates that after complete spinal transection recovery of swimming in fish[39] or walking in amphibian[40] and at least in some birds (e.g. chikens, as shown by popular experience) occurs promptly. In those species which have been studied intensively, particularly fish it is quite clear that the pattern of generation of locomotion in spinal preparation is closely similar to those found in the intact animal[41]. This may persist after deafferentation and even in vitro preparation of the isolated spinal cord[39].

Similarly in many species of non-primate mammals there is a little doubt now that the locomotor activity is controlled by central programmes resident in the spinal cord "central pattern generator" (CPG)[42]. Most of the recent work on spinal stepping has been carried out in acutely transected animals with adjunctive measures such as electrical stimulation of peripheral nerves, dorsal roots or the dorsal columns[43]. Injection of large doses of L-DOPA, the precursor of catecholamine transmitters dopamine and norepinephrine or clonidine a noradrenergic agent, induce stepping in decerebrated and acutely spinalized animals. After spinal shock, stepping reflexes took seven to nine days to return in these mammals.

It was Sherrington[44] who studied the consequences of spinal cord transection in monkeys and found there was immediate cessation of movements in the body segments caudal to the cut. Regarding return of locomotor activity Sherrington did not commit himself clearly. Subsequent investigators[45] transected the spinal cord in a variety of monkeys, but described no activity resembling stepping in any of them. Recently, Eidelberg et al[46]. in two different experimental approaches found that stepping was not possible in either acute or chronic spinal monkeys. In humans, Kuhn[47] reported a long term follow up study of patients with cord injuries with surgical verification of the completeness of transection of the spinal cord. He was unable to show sustained stepping in any of these patients. This seems to argue against the possibility of the programming of locomotor activity by "step generator" circuits endogenous to the spinal cord in humans and the same seems to apply to other primates. Indeed, any proof of the presence of spinal CPG system requires that the cord system involved generates stepping in the absence of descending projections and of reflex afferents as was shown by Graham-Brown[19] and Grillner & Zangger[43]. It is obvious from the presence "moro reflex" and other segmental responses that the spinal cord of infants is not isolated from the rest of the CNS or the periphery. On the above mentioned arguments one can only say that definite evidence for the CPG is minimal in humans and does not satisfy criteria which have been amply fulfilled in non-mammalian forms and in other mammalian groups. This may indicate that step generators are present but require a great deal of tonic facilitatory input from outside the cord or that they have been superceded by other locomotor control mechanisms.

There are conflicting reports regarding peripheral control of locomotion. Three types of rhythmic movements studied recently i.e. locomotion, respiration and mastication have been shown to be independent of afferent input as the rhythmic activity persists after deafferentation and (or) neuromuscular blockade[48]. In contrast, phasic gain changes, or reversal of the responses to peripheral input occur in all of the rhythmic movements. In addition to these effects there are certain constraints placed upon the CPG by input from the brain and from the periphery[49]. Other findings include the effects of hip afferents on the initiation of flexion at the end of the stance phase[50], the importance of unloading of the limb before the swing phase can be initiated[51], the inappropriate response in the contralateral limb resulting from skin stimulation[52], the ability of certain peripheral inputs to entrain the locomotor rhythm[53] and the appearance of a variety of adaptive responses during locomotion depending on the moment of the perturbation in the step cycle[54] are all features that should provide powerful experimental tools for the study of the neurons involved in peripheral control of walking.

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