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A Preliminary Study of Trunk Kinematics during Walking in Normal Subjects

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A PRELIMINARY STUDY OF TRUNK KINEMATICS DURING WALKING IN NORMAL SUBJECTS

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THESIS

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ABSTRACT

The purpose of this study was to systematically describe the three-dimensional trunk kinematics in normal subjects, to establish a baseline for comparison to future research in gait analysis and aid in the identification of pathological gait. Seventeen volunteers between the ages of twenty and fifty, who met criteria for normal subjects, participated in this study. Trunk kinematic data were collected using an optoelectronic technique. An ensemble average of trunk kinematic data in each of the cardinal planes was plotted in degrees of motion versus percentage of gait cycle. A distinct pattern of trunk kinematics during gait was found in this study. Trunk motion relative to the pelvis was of greater magnitude than motion relative to the lab in the frontal and transverse planes. Inter-subject variability ranged from 37% to 644%, with the greatest amount of variability occurring in measurements of trunk movement relative to the lab in all three planes. Stride to stride variability within subjects ranged from 28% to 182%, with the greatest amount of intra-subject variability in trunk movements relative to the pelvis.

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CHAPTER 1

INTRODUCTION

According to Steindler (1955), "walking is a series of catastrophes narrowly avoided" (pg. 67). Although to the casual observer, the walking pattern of an individual without physical disability does not look like an avoided catastrophe, the process of walking is a series of complex events. An individual's walking pattern is referred to as gait. Gait can be described as the process of moving the body mass horizontally by alternating weight bearing and forward motion between the two lower extremities. Many authors have concentrated on the movement characteristics of the lower extremities in describing gait (Steindler, 1955; Lamoreux, 1971; Sutherland, Olshen, Cooper, & Woo, 1980; Inman, Ralston, & Todd, 1981; Boccardi, Pedotti, Rodano, & Santambrogio, 1981; Cappozzo, 1982; Perry, 1992; and Oberg, Karsznia, & Oberg, 1994). Adrian and Cooper (1989) indicated that the body mass first falls forward to initiate gait while the lower extremities prevent an actual fall by repositioning under the body, "establishing a new base of support" (pg. 279).

In describing a complex action, such as gait, it is useful to understand its component parts to simplify the analysis. The gait cycle is the series of events progressing from initial contact of one lower extremity, with forward movement, to the next initial contact of the same extremity. The gait cycle has two major phases, stance and swing. The stance phase, which makes up approximately 60% of the cycle, is divided into subphases of initial contact (0%), loading response (0-10%), midstance (10-30%), terminal stance (30-50%), and pre-swing (50-60%). The remaining 40% of the gait cycle occurs in swing phase and includes the subphases; initial swing (60-70%), midswing (70-85%), and terminal swing (85-100%) (see Figure 1-1). These gait cycle descriptors have been thoroughly defined by Perry (1992). Breaking down the gait cycle into subphases allows researchers and clinicians to identify the critical kinematic and kinetic events occurring during gait. For example, in pre-swing, the knee must passively flex to forty degrees to allow for proper foot clearance and limb advancement (Pathokinesiology Department, Physical Therapy Department, 1989). Kinematics is the description of motions without regard to the forces producing the motions (Ozkaya & Nordin, 1991). Although many authors have described the kinematics of the lower extremities during walking (Steindler, 1955; Lamoreux, 1971; Sutherland et al., 1980; Inman et al., 1981; Boccardi et al., 1981; Cappozzo, 1982; Perry, 1992; and Oberg et al., 1994), there is little objective data on trunk kinematics. Waters, Morris, & Perry (1973) supported this contention.

> Studies of human walking generally concentrate on the most obvious aspect of gait, namely, movement of the lower extremities and connecting pelvis. Less attention is paid to motion of the head and trunk (pg. 167).

Human motion, and in particular trunk motion, is complex. Gross trunk motion results from the summation of coupled rotational and translational movements within each vertebral motion segment. Gross trunk kinematics, however, cannot be generalized from specific spinal arthrokinematics or osteokinematics of a vertebral segment. Research by Nordin & Frankel (1989) has shown that thoracolumbar motion differs from cervical and

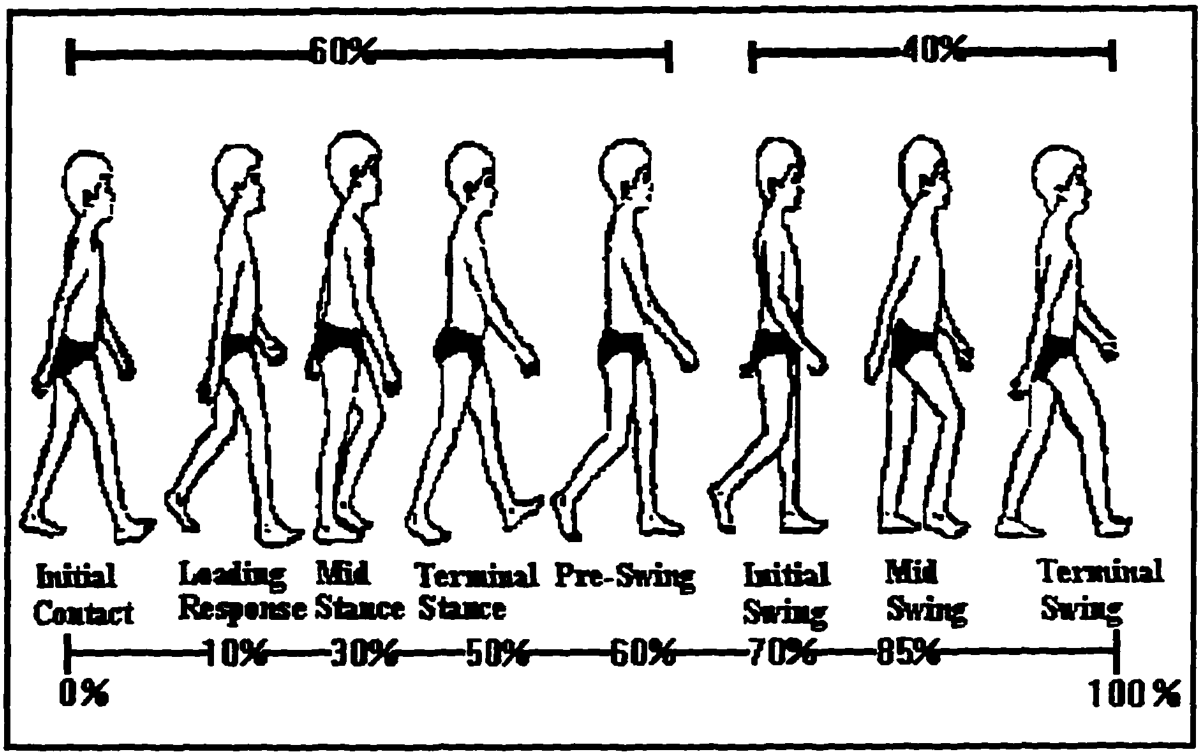


Figure 1-1. Subphases of the gait cycle

sacral movement. For example, the thoracic spine allows for more rotation compared to the lumbar spine which allows greater flexion and extension (Nordin & Frankel, 1989). Fryette (1954) also described trunk osteokinematic movement between vertebral segments as follows: lateral flexion and rotation are coupled to the opposite side when the vertebral column is in a neutral position and to the same side when the vertebral column is flexed or extended. Although spinal segmental movements are coupled in two or more planes simultaneously, generally, assessments of trunk kinematics during gait have measured gross trunk motion (Cappozzo, Figura, Leo, & Marchetti, 1978; Cappozzo, 1981; Cappozzo, 1982; Thorstensson, Carlson, Zomlefer, & Nilsson, 1982; & Krebs, Wong, Jesevar, O'Riley, & Hodge, 1992). Given the complexity of vertebral motion segment kinematics, it is difficult to study these motions in vivo with present day motion analysis systems. Analysis of spinal motion has concentrated on gross trunk kinematics because of this complexity. There is a need to better quantify the three-dimensional kinematics of gross trunk motion during the gait cycle, in order to begin to identify critical kinematic events occurring in the trunk. The identification of critical kinematic events can guide clinicians in their assessment and treatment of pathological gait.

In describing three-dimensional trunk motion, the researcher needs to define a reference system around which movement occurs. Coordinate systems referenced to the body allow motion to be described in the cardinal planes. Three planes of motion exist with reference to anatomical position. These are the cardinal planes: frontal, sagittal, and transverse (see Figure 1-2). Trunk motion which occurs within the frontal plane can be defined as lateral flexion, either toward or away from the stance limb. Sagittal plane

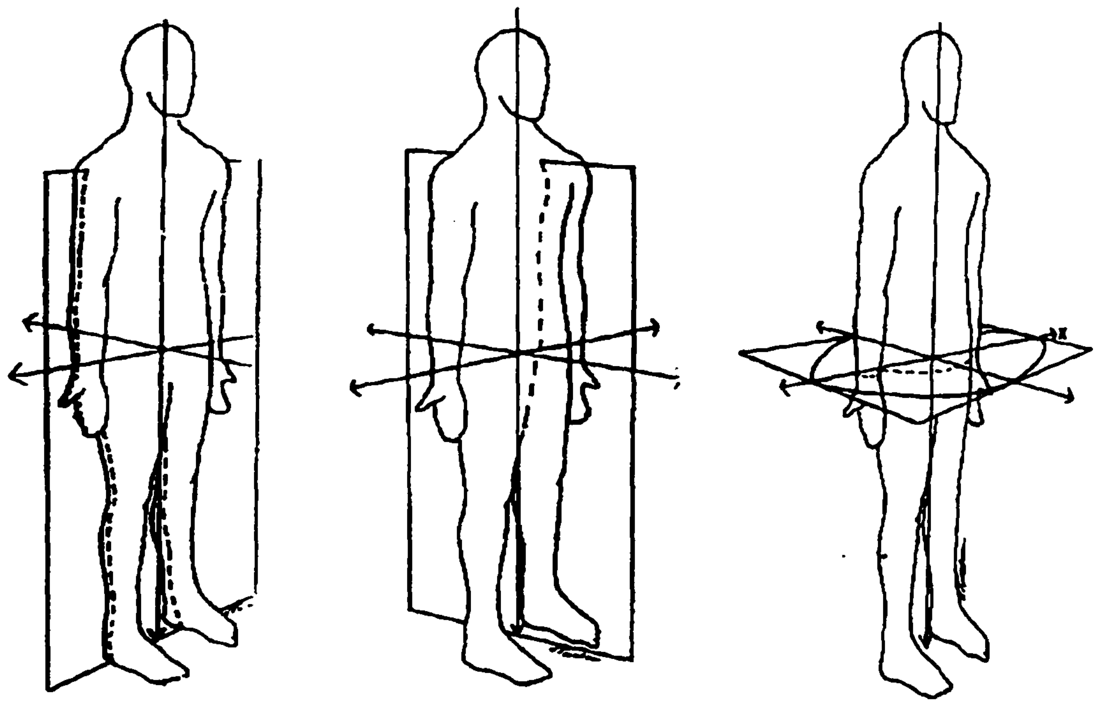


Figure 1-2. Representation of the three cardinal planes. From Joint Structure & Function, by C. Norkin & P. Levangie, 1992, Philadelphia, PA: F.A. Davis Co.

motion includes trunk flexion and extension. Axial rotation occurs in the transverse plane and is described as a rotation toward (retraction) or away from (protraction) the reference limb. Some researchers have measured trunk displacement during gait in only one or two of the cardinal planes (Weber & Weber, 1894; Gregerson & Lucas, 1967; Chapman & Kurokawa, 1969; & Thorstensson et al., 1982), while other researchers have studied vertical trunk displacement (Waters et al., 1973 and Cappozzo, 1981). Krebs et al. (1992) and Crosbie, Vachalathiti, and Smith (1997a) appear to be the only researchers, using modern computerized gait analysis, who have published research on trunk motions occurring in all three planes simultaneously.

Researchers have not yet fully established the function of the trunk during gait. An analysis of the relationship between trunk kinematics and the gait cycle subphases may lead to an understanding of basic trunk function in gait. Thorstensson et al. (1982) stated that "an adequate control of the trunk in relation to the movement of the extremities is essential for efficient and smooth locomotion" (pg. 13). Norkin and Levangie (1992) indicated that the trunk provides a stable base for extremity movement. Most researchers have suggested that the lower extremities drive human locomotion, while the trunk functions primarily as a stabilizer. On the other hand, Gracovetsky (1988) theorized that the trunk was the locomotor engine for human movement. He stated, "the spine and its surrounding tissues emerge as the pervasive element - the primary engine - of locomotion in animals such as ourselves" (pg. 7).

Orthopedic and neurological physical therapy treatment techniques are geared to restoring function in patients with deficits. As gait is one of the most functional tasks, an analysis of pathological gait is imperative for a comprehensive patient evaluation. There is limited objective normative data regarding trunk movement during gait which the clinician can use for comparison. Most current clinical techniques for analyzing gait are based on observation. According to Krebs et al. (1985), "observational kinematic gait analysis appears to be a convenient, but only moderately reliable, technique" (pg. 1027). There is a lack of objective research in analyzing trunk kinematics even among researchers who have had access to more accurate computerized analysis systems. Most research which has utilized computerized motion analysis technology to study trunk kinematics have used small samples which represented a limited and homogenous population (Thorstensson et al., 1982; Thorstensson, Nilsson, Carlson, & Zomlefer, 1984; Opila-Correia, 1990; and Krebs et al., 1992). These researchers generally concluded that a small amount of trunk movement occurred during gait (Thorstensson et al., 1982; Thorstensson et al., 1984; Opila-Correia, 1990; and Krebs et al., 1992). Waters et al. (1973), Chapman and Kurokawa (1969), Thorstensson et al. (1982), and Crosbie et al. (1997a) have demonstrated that there is a repeatable sequence of trunk movement during gait. However, an accepted database of research has not been established which consistently describes or quantifies patterns of trunk motion occurring in the gait cycle.

In past research, trunk movement has been measured relative to time, other body segments, and/or a reference point within the laboratory area (Chapman & Kurokawa, 1969; Carlson & Thorstensson, 1981; Cappozzo, 1981; Thorstensson et al., 1982; and Thorstensson et al., 1984). Only two studies have related trunk movement to percentage of gait cycle. However, neither study described trunk motion with regard to the subphases of gait (Waters et al., 1973 and Crosbie, et al., 1997a). Some studies have identified events in the gait cycle when maximum trunk displacement occurred. However, analysis of trunk position relative to the subphases of the gait cycle has not been completed and is needed for a thorough comparison to pathological gait. A considerable amount of research on trunk kinematics has focused on parameters, other than quantifying displacements, such as; speed of walking (Chapman & Kurokawa, 1969; Lamoreux, 1971; Waters et al., 1973; Cappozzo et al., 1978; Cappozzo, 1981, and Crosbie et al., 1997b), low versus high-heeled gait (Opila-Correia, 1990), age related differences in trunk kinematics (Crosbie et al., 1997b) and treadmill versus free walking (Waters et al., 1973; Carlson & Thorstensson, 1982; Thorstensson et al., 1982; and Thorstensson et al., 1984). While these studies have been important in building an understanding of conditions affecting trunk motions during gait, they do not provide a concrete reference for clinicians to use in their gait assessments, nor do they provide a clear understanding of trunk function during gait.

The purpose of this study was to systematically analyze three-dimensional trunk kinematics relative to the subphases of the gait cycle in normal subjects, to establish a preliminary baseline for comparison to future research in gait analysis and aid in the identification of pathological gait. This data may contribute to an understanding of trunk control during locomotion.

Normative trunk kinematic data during gait will be of value to many health professionals including physical therapists, physicians, biomechanists, and other individuals who utilize gait analysis in developing treatment protocols. Normative data can be used as a reference to identify gait abnormalities. Specifically, the Grand Valley State University/Mary Free Bed Rehabilitation Hospital Center for Human Kinetics Studies has identified a need for normative trunk data to assist in their clinical decision making regarding amputee, cerebral palsy, post-polio, stroke, traumatic brain injury, and other patients with neurological and musculoskeletal pathologies.

CHAPTER 2

LITERATURE REVIEW

Introduction

Research on trunk motion during gait has been documented since 1894. This chapter will chronologically review the various studies which analyzed trunk motions during gait and review other variables which appear to affect an individual's walking pattern. Prior to modern day motion analysis systems, research on trunk movement during gait has differed in recording, description, and explanation methods. Some researchers described trunk movements as displacements in centimeters (Weber & Weber, 1894; Murray, Drought, and Kory, 1964; and Waters et al., 1973), others described trunk movement in degrees of motion (Chapman & Kurokawa, 1969 and Cappozzo, Figura, Leo, and Marchetti, 1978), while a third group of researchers qualitatively described trunk motion (Braune & Fischer, 1987 and Gregerson & Lucas, 1967). Since different approaches have been used to describe trunk motion during gait, it has been difficult to make generalizations regarding spinal function and dysfunction.

History of Trunk Kinematic Research

The cardinal study of trunk kinematics was completed by the Weber brothers in 1894. In this study, a telescope was used to observe the motion of a particular line on the trunk to determine overall trunk movement. These researchers determined the trunk's vertical oscillation to be approximately 32 mm and described an anterior trunk inclination during walking on a horizontal surface (Weber & Weber, 1894). Although results could not be generalized to the greater population because one subject was used and motion was only described in two planes, the Weber brothers inspired further gait research.

In a series of two experiments in 1895, Braune and Fischer, using photography, analyzed trunk motions occurring in the three cardinal planes. Their subject was required to wear an insulated jumpsuit with nitrogen filled glass tubes attached along major body segments. The glass tubes represented the rigid body structure of each individual segment. Electric charges illuminated the tubes to capture segmental positions on film at approximately 30 frames/sec (30 Hz). Lines drawn on photographs connecting hip joints and shoulder joints were compared to assess trunk rotation. Sagittal and frontal plane motion was determined by comparing both shoulder and hip joint lines with the movements of the lower extremities. Braune and Fischer (1987) recorded minimal trunk movement in all planes. Movements in the transverse plane, however, were not quantified because there were irregularities in their data. Sagittal plane movement was described as a forward or backward tilt. Forward tilt occurred maximally before initial contact while maximum backward tilt occurred at mid-stance. Frontal plane motion was described as a trunk tilt either toward or away from the stance limb. Braune & Fischer (1987) described a maximum tilt of the trunk, toward the stance limb, shortly after heel strike. These researchers reported that following this maximum excursion, the trunk returned to neutral. Limitations of the study included: (a) Trunk motions may have been inhibited due to the intricate measurement apparatus and the subject's fear of potential electrocution with movement, (b) Motions were quantified only in one plane, and (c) There was only one subject. Therefore, generalizations could not be made to the general population.

However, Braune and Fischer pioneered two concepts related to studying trunk movement during gait. One, body segments could be thought of as rigid bodies, enabling kinematic calculations using classical mechanics principles. Two, they developed a stereophotogrammetric technique which was a precursor to optoelectronics, a technique used in modern day gait analysis.

In 1964, Murray, Drought, and Kory conducted a comprehensive gait study on males to establish parameters for normal gait. Sixty subjects were first divided into five categories by age and then further divided into sample groups by height (short, medium, and tall). They used interrupted light photography to record the position of reflective targets on ambulating subjects. The following gait determinants were studied: step and stride length, foot angle, and kinematics of the trunk and lower extremities. Trunk kinematics were analyzed and described with respect to movement occurring in the cardinal planes and in the vertical direction. The authors also analyzed the difference in pelvic and thoracic rotation to describe the amount of counter-rotation which occurred within the varying height and age groups. The results of the kinematic analysis showed strikingly similar data for repeated trials with the same subject and between subjects, except for transverse rotation of the trunk. The pattern found in the transverse plane was variable. Tall subjects showed the least amount of thoracic rotation but the greatest amount of pelvic rotation, while data on the other height groups was not conclusive. The authors were unable to calculate the average time for peak thoracic or pelvic rotation because of this inter-subject variability. The authors suggested that "these [transverse] excursions are produced more by an individual's attitude of locomotion than by mechanical demands" (pg. 358). Since different height groups showed differing amounts of pelvic and thoracic excursion, no proportional pattern in the counter-rotation data could be shown. In the frontal plane, they reported lateral trunk oscillations occurring toward the stance limb, with a mean peak magnitude of 6.0 ± 1.7 cm at mid-stance. The measurements taken in the sagittal plane represented forward displacement and not trunk flexion or extension. The researchers found an oscillating pattern of forward displacement with two peaks of forward movement occurring "shortly after heel strike [initial contact] during periods of double limb support" (pg. 349). In the vertical direction, two periods of maximum excursion were found to have occurred during each period of single limb support "as the trunk rotates over the fixed foot" (pg. 349). The authors calculated an average vertical displacement of 4.9 ± 1.1 cm. No correlation between age and kinematic variables were found.

Subsequent assessment of trunk movement during gait involved an in vivo study in which Gregerson and Lucas (1967) measured axial rotation. They analyzed spinal movements by inserting pins into spinous processes at different segmental levels and measured the movement between the pins. Although segmental movement measurements were inconsistent, a general pattern of trunk movement was found: (a) An opposite rotation between the shoulders and pelvis was found during treadmill walking at 4.38 km/hr, (b) The magnitude of shoulder rotation was found to be less than pelvic rotation, and (c) The T_7 level remained neutral throughout gait, representing the pivot point between pelvis and shoulder motion. Due to small sample size and an inconsistent testing protocol, results of segmental movements were not generalizable to the general population.

In 1969, Chapman and Kurokawa described the transverse rotation of the pelvis and shoulders (upper trunk) as subjects walked on a treadmill at three different speeds. They also compared upper trunk rotation in relation to the pelvic rotation, which they defined as counter-rotation. As subjects walked faster, the amount of upper trunk rotation decreased while the amount of pelvic rotation and trunk counter-rotation increased. Mean upper trunk rotation decreased from 7.8° to 5.8° with changes in speed from 2.93 km/hr to 5.86 km/hr, respectively. Average pelvic rotation increased from 7.6° to 13.2° and mean counter-rotation increased from 9.4° to 17.0°, during the same test. Chapman and Kurokawa (1969) indicated that counter-rotation was "not exactly 180° out of phase" (pg. 39). This meant that the upper trunk was not moving synchronously in opposition to the pelvis. The authors admitted that they had difficulty quantifying rotations during gait because the subject was "tethered by electrical wiring to the recording equipment" (pg. 52) . Furthermore, this study was limited by the fact that it only described motion in one plane.

Waters et al. (1973) studied trunk kinematics during gait by using transducers attached to subjects at the head, T_{10}, and S_2. The transducers registered trunk displacement in the lateral, vertical, and progressional directions while subjects walked on a treadmill at three different speeds ranging from 2.92 to 5.84 km/hr. Measurements were related to percentage of gait cycle and were correlated with differences in walking speed. Waters et al. (1973) found that increases in displacement of the trunk in all directions were proportional to walking speed, except excursions in the lateral direction. "The amplitude of lateral displacement is relatively unchanged at increasing walking speeds" (pg. 171). Lateral displacements were found to move, on average, 4.5 cm away from the swinging limb, at 62% of the step cycle and continued until "the same time in the next step cycle" (pg. 170). There were no differences found between the magnitudes of pelvic and head displacements in the lateral direction. Average vertical trunk displacement was found to be approximately 4.2 cm. There was no difference found between vertical displacement at the pelvis and head, i.e. the head and pelvis move together in the vertical direction. "Maximum downward displacement occurred at 17 % of the step cycle [double support] and maximum upward displacement occurred at 68% of the step cycle [single support]" (pg. 170). Unlike vertical displacement, movements in the progressional direction were not coupled between the head and pelvis. Progressional displacements were measured as the amount of upward or downward movement of the various segments (S_2, T_{10}, and head). Waters, et al. (1973) found that all segments displaced sinusoidally, with excursions in both directions. However, the amplitude of excursions decreased from 2.6 cm at S_2 to 0.5 cm at the head. Limitations for this study included: (a) Only five subjects were assessed and (b) Results for lateral and vertical displacements were reported in relation to step cycle. However, the authors did not objectively define "step cycle". Therefore, it was difficult to interpret where in the gait cycle, the displacements in these three planes occurred.

It was not until 1978 that Cappozzo, Figura, Leo, and Marchetti utilized the stereophotogrammetric technique developed by Braune and Fischer in analyzing motions of the trunk. Stereophotogrammetry is the "three-dimensional reconstruction of the instantaneous position of a moving point in a laboratory coordinate system" (Cappozzo, 1984). Light emitting diodes were attached to the subjects' trunk and upper and lower extremities. Using four open-shutter cameras positioned symmetrically at the four corners of the lab, trunk movements in the frontal, transverse, and sagittal planes were calculated from photographs of targeted anatomical landmarks. Measurements of trunk motions were related to movements of the pelvis, described in relation to percentage of gait cycle, and correlated with changes in walking speed. The authors stated that "when speed of progression increases, the movement pattern changes" (pg. 278), however, they did not specify if this relationship between kinematics and speed were found in all the cardinal planes. In their discussion, they cited research by Waters et al. (1973) as having consistent findings with their study. One might deduce that the movement changes which were correlated with walking speed were within the sagittal and transverse planes, as these were the planes which Waters et al. (1973) investigated. Limitations in this study included: (a) Only two subjects were used in their design and, (b) Subjects' movements may have been inhibited due to imposed upper extremity flexion during gait (the arms were flexed to enable researchers to view all targets during the gait cycle).

Using similar methodology, Cappozzo (1981) found a repeatable pattern of head and trunk displacement during walking, which supported results from the 1978 study. In 1981, Cappozzo used harmonic analysis to differentiate two patterns of trunk movement, intrinsic and extrinsic. He described the intrinsic pattern as a "stereotyped" movement in the antero-posterior, medio-lateral, and vertical directions that was consistent within and between subjects. The extrinsic pattern was described as "not inherent to the locomotor act in its essential form but rather ascribed to some sort of external disturbance" (pg. 417). The extrinsic pattern was found to have a high degree of variability due to factors such as, anatomical or functional asymmetries and environmental disturbances. Along the anteroposterior axis, the pelvis was found to displace further than the shoulder or head, while in the medio-lateral axis, head and shoulders underwent a larger excursion than the pelvis. Results from Cappozzo's 1978 and 1981 studies were quantified in unconventional terms using Lissajour plots and harmonic analysis which have not been practical for clinicians to use.

Current Trunk Kinematic Research

Whittle (1991) stated, "... photography remained the method of choice for the measurement of human movement [lower extremities] for about 100 years until it was displaced by electronic systems" (pg. 161). In reference to photographic analysis of the trunk, Cappozzo (1984) stated, "measurements in the strict sense could not be sufficiently accurate" (pg. 28). In the past, small amplitudes of trunk motion have been difficult to detect and consistently quantify using photographic techniques. Small amplitude movements can now be detected through the use of optoelectronic techniques. Optoelectronic motion analysis consists of using high speed videography in conjunction with computer video processing software to identify three-dimensional positions of anatomically placed targets. Additional processing software uses these three-dimensional coordinates to calculate angular displacements of body segments during gait. Some current researchers and clinicians have taken advantage of optoelectronics to obtain objective kinematic data with a higher degree of accuracy compared to observational analysis (Thorstensson et al., 1982; Krebs et al., 1992; Opila-Correia, 1990, and Crosbie et al., 1997a). Unobservable three-dimensional trunk movements have been more accurately quantified in the cardinal planes (sagittal, frontal, and transverse) using optoelectronic systems (Krebs et al., 1992; and Crosbie et al., 1997a).

Until the optoelectronic technique was utilized, researchers had difficulty consistently quantifying trunk kinematics in the cardinal planes during gait. High speed videography has revealed sagittal plane movement magnitudes between two and ten degrees (Thorstensson et al., 1982; Krebs et al., 1992; Opila-Correia, 1990; and Crosbie et al., 1997a). Thorstensson et al. (1982) described two oscillations of movement (forward and backward) in the sagittal plane during one gait cycle. Backward displacement began at initial contact and continued through the initial phase of double support. Forward displacement began at the end of the initial phase of double support (Thorstensson et al., 1982). Krebs et al. (1992) supported Thorstensson's finding by describing "patterns [which] typically included a flexion peak near each heel strike"(pg. 40). However, Krebs reported that maximum extension occurred during single-limb support, rather than flexion as Thorstensson found. Crosbie et al. (1997a) also agreed that there were two oscillations in the sagittal plane which occurred during the gait cycle. He reported maximum trunk flexion at heel strike, however, maximum trunk extension was found during single-limb support. Crosbie's work supported the findings of Krebs et al. (1992).

Researchers have disagreed regarding trunk movements in the frontal plane. Opila-Correia (1990) denied that there were any significant patterns in the frontal plane during gait. Contrary to Opila-Correia (1990), Krebs et al. (1992), Thorstensson et al. (1982), and Crosbie et al., (1997a) stated that there was a predictable pattern of frontal plane motion during gait. They found that the trunk was displaced toward the stance limb at heel strike, and reached maximum magnitude at contralateral toe-off. The magnitude of these motions were between two and nine degrees (Thorstensson et al., 1982 and Crosbie et al., 1997a). Crosbie et al. (1997a) described trunk motions which occurred at three spinal regions (pelvis, lumbar, and thoracic) and noted a greater " peak-to-peak range of motion for lateral flexion" (pg. 10) at the lumbar segment through the gait cycle.

Optoelectronic systems have helped to quantify transverse trunk motion both relative to the pelvis and relative to the coordinate system in which they were recorded. Krebs et al. (1992) described transverse plane movement of the trunk during gait as "rotating so that the ipsilateral shoulder was posterior to the heel-strike [initial contact] limb, nearly directly over the foot at mid-stance, and maximally anterior to the stance limb near toe-off [pre-swing]" (pg. 40). At pre-swing and initial contact these motions were shown to reach a maximum of ten degrees. Krebs et al. (1992) reported transverse trunk motion relative to both the pelvis and room coordinates, and found a greater variability of trunk motion relative to the pelvis. Crosbie et al. (1997a) showed a similar pattern of trunk motion in the transverse plane, but reported only two degrees oscillation about a neutral axis.

Theories on Trunk Function during Gait

There appears to be a controversy regarding the function of the trunk during gait. On one side of the debate, researchers have asserted that the trunk functions as a stabilizer for motions of the lower extremities or a dampener to ground reaction forces produced during walking. Chapman and Kurokawa (1969) suggested that the muscles of the trunk and shoulders inhibited the rotatory forces which occurred at higher walking speeds. They postulated that if shoulder motion were passive in response to pelvic rotation, shoulder rotation would increase proportionately to pelvic motion. They did not find this increase in shoulder rotation in their study, but suggested that the forces produced by the lower extremities were dampened due to the "mechanical characteristics of the linkage between the pelvis and shoulder girdle" (Chapman & Kurokawa, 1969, pg. 57). Cappozzo et al. (1978) agreed with Chapman and Kurokawa's theory regarding the dampening function of the trunk and further assumed that dampening occurs to decrease the effect of ground reaction forces on the brain. He stated, "the reduction of head and trunk energy is to lighten the burden on important sensory organs, such as the eyes and labyrinth, that play a fundamental role in controlling the movement that is being performed" (pg. 279). In 1972, Waters and Morris suggested that it was the ground reaction forces which caused the trunk muscles to 'react' during gait. They indicated that the center of gravity for the entire body resided within the trunk at the level of S_2. Using electromyography during gait testing, they identified back extensor activity as the most probable event in retarding the forward flexion moment created by the trunk falling in front of the line of the center of gravity.

> Ground reaction forces during walking are transmitted through the lower extremities and the pelvis to the trunk. These forces tend to flex the trunk forward because of the relatively anterior location of the center of gravity of the body. However, it seems probable that the [back extensor muscles] act to oppose the tendency of the trunk to flexion (Waters & Morris, 1972, pg. 198).

Waters and Morris did not indicate whether the trunk response to ground reaction forces also occurred to dampen the mechanical forces induced by the lower extremities. In 1981, Cappozzo hypothesized that dampening must occur because the trunk did not move rigidly with the pelvis, if it had, the difference in mechanical energy between the trunk and lower extremities would have been higher. Townsend (1981) looked at the mechanics of the torso and also hypothesized that dampening occurred, but could not identify the trunk as the primary dampening agent.

On the other side of the debate, Gracovetsky (1988) stated that the trunk was the primary initiator of gait; that it fueled locomotion. He developed his theory by exploring the evolutionary history of animals in motion. Gracovetsky suggested that, through years of evolution, humans have evolved to combine the lateral flexion of the fish with the exploitation of gravity to power locomotion. He supported his theory by arguing that it is the transverse motion of the spine, coupled with lateral flexion, which produces a characteristic pelvic rotation. It is pelvic rotation which propels movement of the lower extremities. Further, Gracovetsky theorized that through natural selection, humans have developed a very efficient gait. Efficiency is obtained through exploitation of gravity and ground reaction forces which act on the posterior ligamentous system of the spine. The passive elastic system of the posterior ligaments and fascia allows transfer of kinetic to potential energy and vice versa for smooth locomotion. Gracovetsky disagreed with other researchers' assertions that the spine was a passive dampener of ground reaction forces, but cited evolutionary evidence that the spine was more than a quiescent spectator during gait. Gracovetsky suggested that "the argument is not whether bipedalism requires a human spine but, rather, if human gait can be achieved with a passive, fused or otherwise disabled spine" (pg. 288). He indicated that when a patient wore a spinal brace, restricting the natural movement of the spine, their gait was altered. Additionally, Gracovetsky postulated that human gait does not require the use of the lower extremities. He cited the example of a patient who was a double above knee amputee and was able to walk without prostheses. This individual's trunk motions were similar to the trunk motions of an individual who walked on two legs, except in amplitude of trunk motion. The individual with the double amputation demonstrated a higher amplitude of trunk motion. Gracovetsky contended that "the legs serve to amplify the motion of the spine; when they are absent, the motion of the trunk must become more dynamic in order to maintain a reasonable forward velocity, but there is no need to change the basic pattern of motion"(pg. 365). According to Gracovetsky, it appears that the dynamic interplay of the spine and the surrounding soft tissues are essential for the fluidity of human gait.

Despite the number of researchers in support of the trunk functioning to dampen ground reaction forces produced during gait, there is still no direct evidence to support either theory regarding trunk function during gait. Developing a normative database on trunk kinematics may provide some of the information needed to determine trunk function during gait.

Other factors considered in analysis of the trunk during gait

Speed

To control for variability in kinematic data and accommodate for bulky measuring equipment, many researchers have utilized a treadmill in their studies. In treadmill gait, a subject is forced to walk at a predetermined and continuous pace. The question has been posed as to the speed which best represents a "normal" walking speed. A 1958 study by Ralston determined that 4.38 km/hr was the optimal speed for minimizing energy consumption and maximizing comfort. Many gait studies that have used a treadmill have chosen this speed (Gregerson & Lucas, 1967; Chapman & Kurokawa, 1969; and Waters et al., 1973). Lamoreux (1971), in writing on the importance of gait analysis, proposed that each subject in a study may have many different gait patterns depending on speed. He focused more on the differences in kinematics than on efficiency, stating that the "energy cost deviating from the so-called optimum is not great" (pg. 8). Kinematic changes resulting from varying speeds during gait have been observed by numerous researchers (Murray et al., 1964; Chapman & Kurokawa, 1969; Waters et al., 1973; Cappozzo, 1981; and Crosbie et al., 1997b). Crosbie et al. (1997b) found that there was an increased motion between trunk segments with increased speed. Most changes in trunk kinematics relative to speed have been documented in the transverse plane. With the exception of Chapman & Kurokawa (1969), who found changes in the pattern of trunk movement in the transverse plane with increasing speed, most researchers found that only the amplitude of trunk movements changed with increases in speed (Murray et al., 1986; Waters et al., 1973; Cappozzo, 1981; and Crosbie et al., 1997b).

Gender

Most studies which have analyzed trunk kinematics have predominately used male subjects (Weber & Weber, 1894; Braune & Fischer, 1895; Gregerson & Lucas, 1964; Murray et al., 1964; Waters et al., 1973; Cappozzo et al., 1978; Cappozzo, 1981; Cappozzo, 1982; Thorstensson et al., 1982; and Thorstensson et al., 1984). A relatively small amount of research has been performed addressing differences in trunk and pelvic kinematics between men and women at any walking speed. One of the first studies to look at the male/female difference was Chapman and Kurokawa (1969). They found no significant differences between gender, but "at a moderately fast walk, the pattern of rotation was sufficiently consistent and individualized [between genders]" (pg. 49). Though this was not statistically significant, when walking patterns were graphed, the different gender graphs were visibly discernible. Gender effects on trunk motion during gait have also been studied by Crosbie et al. (1997b). These researchers found that gender had little effect on trunk motion. Krebs et al. (1992) included both male and female subjects in their study (5 males, 6 females), but did not report differences in male and female trunk kinematics. It is premature to postulate that there are no differences in gait between the genders, as past researchers have not comprehensively studied this variable. Although kinematics during gait may differ with gender, analysis of this variable is beyond the scope of this study.

Trunk Movement in Clinical Assessment and Treatment

Abnormal trunk or pelvic movement patterns are often observed in the gait of patients with orthopedic disorders. Patients with acute spinal or pelvic dysfunction may manifest altered gait patterns as a result of pain, muscle imbalance, soft tissue restrictions, or bony malalignment. For example, patients with acute herniated disc injury ambulate with an increased lumbar kyphosis and a lateral trunk shift (Hertling and Kessler, 1990). "The sacroiliac joints and symphysis pubis are closely linked functionally to the hip and intervertebral joints and therefore affect and are affected by movements of the trunk and lower extremities" (Norkin and Levangie, 1992, pg. 158). During ambulation, the sacroiliac joints experience shearing forces as a result of lateral pelvic tilt. Patients with sacroiliac joint dysfunction may not be able to compensate for these shearing forces that accompany weight bearing during ambulation. As a result, the pelvis may become painful and unstable and increase the stress on the vertebral column as well as the hip joints. Pelvic instability may be identified in observational gait analysis as a shortened step length or decreased gait speed. Identification of abnormal trunk and pelvic movements during gait can assist the clinician in determining the source of orthopedic dysfunction, aiding in clinical decision making. The return of normal spinal kinematics, as identified by three-dimensional gait analysis, can also serve as an objective outcome measure.

Patients with neurological disorders may also exhibit altered trunk kinematics during gait. Many techniques used in the treatment of neurologic disorders begin by facilitating 'normal' trunk movement. It has been suggested that the trunk serves as the base for all body movements (Davies, 1985 and Voss, Ionta, & Myers, 1985). This means that in order to control the extremities, one needs control over the base, the trunk. Bobath, who brought to bear neurological developmental treatment (NDT), concentrated on trunk retraining with the intention that control of trunk movement would lessen the dysfunctional movement patterns of the extremities (Davies, 1985). In NDT, the trunk is retrained using repeated patterns of diagonal and rotational movements. Once the individual can control these movements, treatment moves to more distal segments. These concepts are used not only for retraining of activities of daily living, but also include the most functional task, gait. Treatments to facilitate gait are directed toward control of rotations between the trunk and pelvis for smooth and coordinated lower extremity movement. Temporal gait parameters, such as cadence, velocity, and step length, are often used as a reliable measure in studies of the efficacy of neurological treatment techniques. Although this is a quantitative way to look at function, it does not account for kinematic variables which may influence the efficiency and quality of gait. Goal writing for lower extremity dysfunction during gait is often aimed at improving specific critical kinematic events which are lacking. For example, if an individual has foot drag during swing phase, a short term goal may be the following: Patient will ambulate to and from the bathroom (50 ft.) without toe drag at least 50% of the time within two weeks. Understanding how the trunk moves during the gait cycle is the first step in identifying the critical kinematic events that occur in the trunk during the gait cycle. Knowledge of critical trunk kinematic and kinetic events could guide clinicians in their assessment and treatment of individuals who have pathological trunk movement which affects their gait pattern.

Summary

In summary, past research on trunk movement during gait described motion occurring in the three anatomical planes, however, a normalized database on trunk kinematics has not been compiled. Conclusive descriptions of trunk position throughout the gait cycle, in particular, have not been well researched. Researchers have been unable to generalize to 'the greater population' due to use of few subjects and unreliable techniques. Some previous studies have concentrated on defining trunk movement with changes in gait speed during treadmill walking (Chapman & Kurokawa, 1969; Waters et al., 1973; Cappozzo et al., 1978; Cappozzo, 1981; Cappozzo, 1982; Carlson & Thorstensson, 1982; Thorstensson et al., 1982; Thorstensson et al., 1984; and Krebs et al., 1992). It can be concluded from these researchers that controlling gait speed during kinematic analysis may decrease the amount of variability between subjects' kinematic data. However, Murray et al., 1966 indicated that controlling speed may change an individual's normal gait.

Methods of research have evolved from the use of simple photography to modern day use of optoelectronic systems to quantify trunk movements. Despite cumbersome techniques used by past researchers, their ideas have begun to create a base from which to analyze the role of trunk movement during gait. Researchers have found that minimal trunk movement occurred during gait. These trunk movements were found to follow a repetitive sequence. General patterns of trunk movement during locomotion have been described. However, normative values for movement in all planes relative to the subphases of the gait cycle have not been established. Therefore, the purpose of this study was to establish a preliminary normative database for three-dimensional trunk movement relative to the subphases of the gait cycle.

CHAPTER 3

METHODOLOGY

Subjects

Seventeen normal subjects participated in this study. Normal subjects were defined as individuals between the ages of twenty and fifty who had been without incidence of pain or orthopedic injury within the past six months. Subjects were recruited on a volunteer basis via advertisement at local universities and hospitals. Prior to the study, subjects received a letter and brochure informing them of the date of testing and descriptions of the study's purpose and procedures (Appendix A and B). On the day of testing, participants were asked to fill out a past medical history form and underwent a preliminary clinical examination (Appendix C and D). Admission to the study was based on results of past medical history and clinical examination. Exclusion criteria based on past medical history and clinical examination are defined in Appendix E. A history of the following criteria also excluded subjects from this design: spinal surgery, spondylolisthesis, ankylosing spondylosis, neurological injury to the spinal cord and nerves, and fractured vertebrae or herniated disc, or other disorders, dysfunctions, or diseases of the spine. Subjects were asked to sign a consent form prior to data collection (Appendix F).

Instrumentation

Cameras

Movements of the trunk and lower extremities were recorded with the Elite four-camera optoelectronic system.[1] Each camera contains a ring of light emitting diodes (LEDs) which surround the lens. Infrared rays are emitted from the LEDs and reflected back to the camera lens from the targets placed on the subject. Targets are constructed of wooden spheres covered with 3M Scotchlite Brand High Grain 7610 retroreflective tape[2]. Camera measurements, synchronized with LED impulses, were sampled at 100 Hz. From the reflected signal, each camera generates an object image on a two-dimensional plane. A video processor sends synchronous camera signals to a computer so that corresponding frames of video data from each camera are processed simultaneously. At least two cameras are needed to identify the individual targets' three-dimensional position in space. Mathematically, this is accomplished through direct linear transformation which will be discussed in a later section. The Elite system has a reported accuracy in identifying target location within 3.2 mm (Ehara, 1995). Cameras were placed at the four corners of the designated testing space (see Figure 3-1). Prior to data collection, calibration was performed to determine the cameras' orientation in relation to the working volume and the relative position of each camera to another (see Figure 3-2).

Two Panasonic X20 Digital Zoom Super VHS video cameras[3] collected video images of the subjects' gait in the frontal and sagittal planes simultaneously for observational documentation. Images were fed into a Panasonic Digital Effects Generator[3] so that both sagittal and frontal plane motion could be viewed on one screen. The video images will be used in future research by the Human Kinetics Laboratory, but

[1] Elite, BTS, Milano, Italy
[2] 3M Health Care, Medical Supply Division, St. Paul, MN
[3] Panasonic Co., Matushshita Electrical Corp., Secaucus, NJ

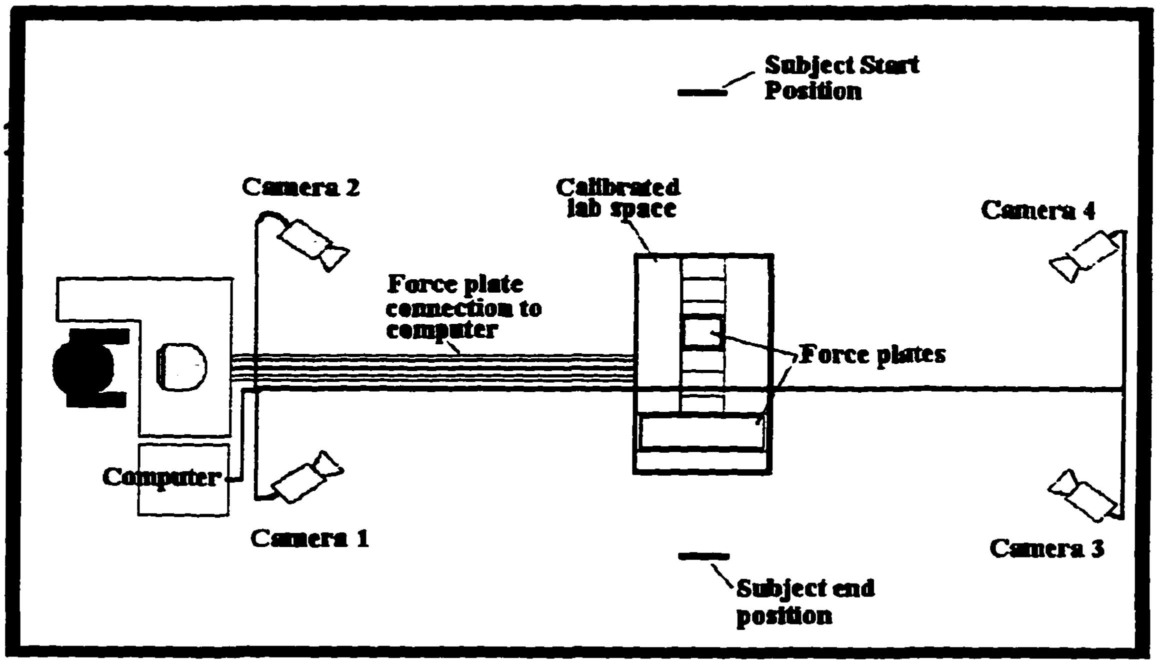


Figure 3-1. Laboratory, camera, and force plate configuration

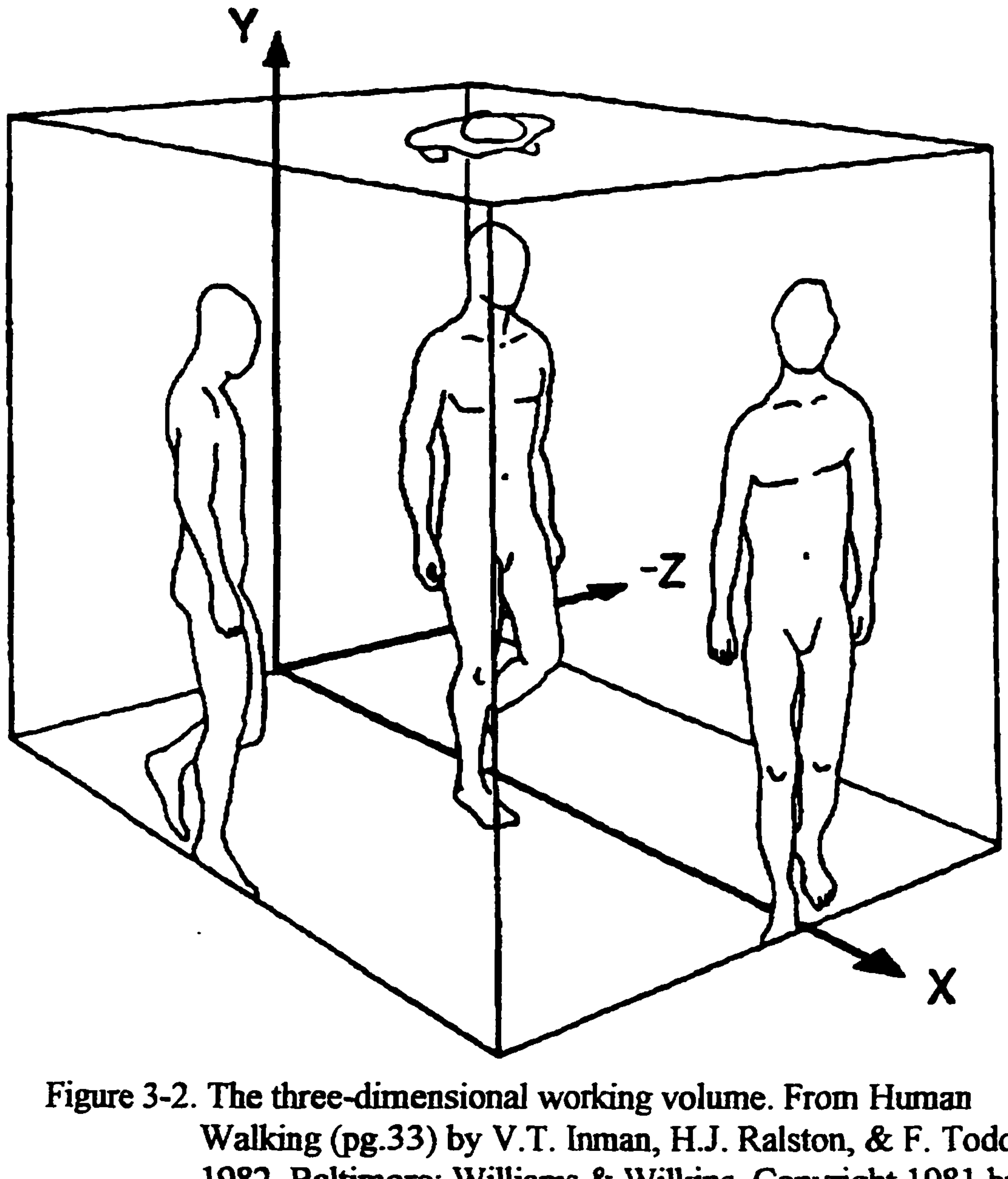


Figure 3-2. The three-dimensional working volume. From Human Walking (pg.33) by V.T. Inman, H.J. Ralston, & F. Todd, 1982, Baltimore: Williams & Wilkins. Copyright 1981 by Williams & Wilkins.

were not analyzed in this study.

Force Plates

To identify trunk movements relative to the gait cycle, two Advanced Mechanical Technologies, Inc. (AMTI) force plates[4] were used to signal the beginning and end of the gait cycle. The plates were placed flush with the lab floor and covered with carpeting so they were not detectable to subjects (see Figure 3.1). Collection of force plate data occurred synchronously with kinematic data. The AMTI force plate collected data when 15 N (3.37 lbs) were exerted on the plate. This quantity was chosen to decrease the incidence of false triggers.

Electromyography (EMG)

EMG data were collected on all subjects for use in future research by the Center for Human Kinetic Studies, but were not analyzed in this study. A TELEMG Multichannel Electromyography system[5] recorded the electrical activity of trunk muscles during the gait cycle at a frequency of 500 Hz. Surface electrodes made of silver/silver chloride with a differential impedance of one megaohm were placed over specific trunk muscles. These trunk muscles included: bilateral erector spinae at the level of L_{3-4} and T_{8-9} and bilateral external obliques. A lightweight patient unit collected pre-amplified analog signals from the surface electrodes and sent them through a fiber-optic cable to the base unit for additional amplification, digital conversion, and filtering. Six EMG trials were performed following kinematic data collection, in order to minimize error in kinematic data collection. The patient unit may have restricted subjects' trunk movements or

[4] AMTI, Advanced Medical Technologies Inc., Newton, MA
[5] TELEMG, Bioengineering Technology Systems, Milano, Italy

obstructed the camera's view of trunk targets.

Procedures

Targeting Pilot Study

Prior to subject testing, a comparison of three trunk targeting protocols was performed. Protocol one included measurement of trunk movement from targets placed on bilateral mid-clavicles and spinous process of T_4. Protocol two included targeting of the sternal notch, xiphoid process, and spinous process of T_4. Protocol three included placement of targets on the sternal notch and the spinous processes of T_4 and T_9. Two researchers had all targets from each protocol placed on these anatomical landmarks during the pilot test. The researchers walked within the calibrated testing volume and data were collected and processed as per the procedure outlined in this methodology. Angles in each of the cardinal planes were calculated from each protocol. Patterns of trunk movement from each protocol were similar. However, the first protocol was excluded from this study, due to possible extraneous movement of clavicular targets due to arm swing and shoulder movement. This additional movement may have contributed to more trunk movement measured than actual. Protocol two was excluded from this study as there was a concern of camera's not seeing the xiphoid target in full-figured women. Therefore, protocol three was established as the targeting protocol for this study.

Calibration

The first step in collecting kinematic data is to define a working volume in which movement occurs. In order to define the working volume, a rigid grid system with retroreflective targets placed at known X, Y, and Z coordinates was positioned within the working volume. The grid system represented the estimated size of the subjects' stride length and shoulder height. Once this space was defined, calibration allowed the Elite system cameras to determine their own position relative to the working volume using direct linear transformation (DLT). Known camera position is necessary for determining the three dimensional coordinates of the targets. Internal parameters of the camera are used with known camera positions to eliminate the unknowns in equations used to calculate target coordinates on moving subjects.

Direct Linear Transformation

Direct linear transformation is a mathematical algorithm used to accurately identify the three-dimensional position of targets placed on the subject. "Cameras are only capable of viewing a three dimensional image as a two dimensional projection; a minimum of two cameras must be synchronized and [both view the target] in order to establish the three dimensional position of an object in laboratory space" (Ellexson, Nawrocki, & Schober, 1995). As targets reflect the infrared rays back to the camera lens, the image is viewed on the two-dimensional plane of the camera. Two synchronized camera images of each target are combined through direct linear transformation to develop the three-dimensional target position relative to the laboratory coordinate system. The target position is calculated by creating a vector from one camera eye to the two-dimensional image of the target and projecting this vector out into three-dimensional space from that camera's position. The second camera synchronously completes the same process to calculate the target's image. The location of the target is calculated at the intersection of the projected vectors from the two cameras in three dimensional space (see Figure 3-3).

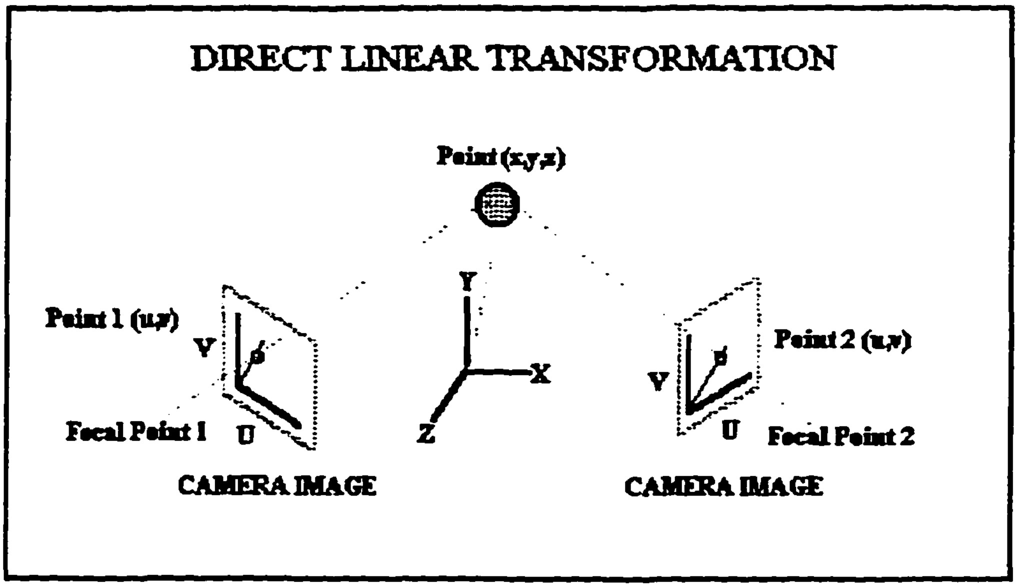


Figure 3-3. Illustration of Direct Linear Transformation. A process of establishing three-dimensional coordinates from two-dimensional projections.

Clinical Examination

A clinical examination was performed to determine which subjects met the criteria for normative data collection. Information regarding patient past and current medical history was collected via questionnaire (Appendix C). A clinical examination was used to determine if the subjects' general trunk and lower extremity range of motion, lower extremity strength, and posture were within normal limits. The clinical examination consisted of observation of posture, tests to determine strength and range of motion for the lower extremities, leg length measurements, trunk flexibility, a standing forward flexion test, and a quick screen for scoliosis (Appendix D). See Appendix E for exclusion criteria. Using a standard tape measure and caliper, other anthropometric measurements were gathered for use by the Human Kinetics Laboratory, but were not analyzed in this study. Procedures for gathering anthropometric measurements were consistent with those defined in Appendix G (Appendix G & H).

Test Preparation

Subjects were required to wear shorts and a top which revealed the required trunk bony landmarks for targeting. Targets were placed directly on the subjects' skin using 3M hypoallergenic adhesive tape in the following areas: spinous process of T_4 and T_9, sternal notch, bilateral ASIS's, spinous process of S_2 (midpoint between bilateral PSIS's), thigh wand on lateral mid thigh, lateral condyle of femur, tibial tuberosity, distal anterior shank of tibia, distal posterior shank of tibia, calcaneus, lateral foot posterior to 5th metatarsal head, and medial foot posterior to the 1st metatarsal head (see Figure 3-4).

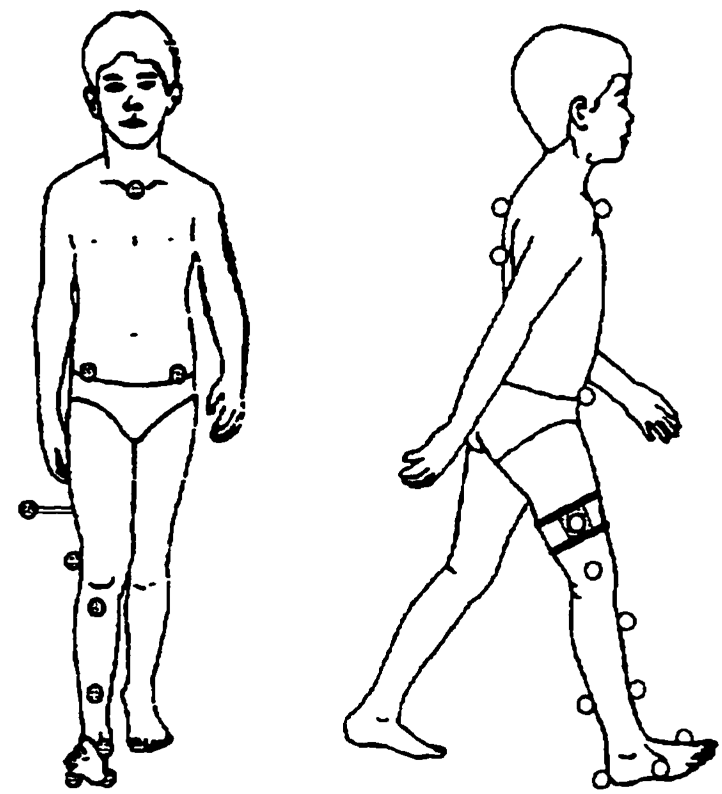


Figure 3-4. Illustration of targeting placement protocol

For those trials where EMG data were collected, subjects' skin overlying the following muscles was shaved and cleaned with an alcohol swab: bilateral erector spinae (L_{3-4}) 2 cm lateral to the spinous processes at the level of the iliac crest, bilateral erector spinae (T_{8-9}) 2 cm lateral to the 9th thoracic spinous process, and bilateral external obliques midway between the lower costal margin and the midpoint of the iliac crest (Winter, 1991). Shaving and cleansing of the overlying skin was done to optimize the conduction of the muscles' electrical signal through the skin to the electrode and minimize electrical noise resulting from various factors such as hair, dirt, and oil. Using a bipolar technique, disposable self-adhesive electrodes were placed approximately 30 mm apart, parallel to the muscle fibers. The electrode lead wires were also taped down to the subjects' skin to reduce the amount of noise resulting from movement of the wires while the subject was walking.

Testing Protocol

Prior to data collection, subjects had an opportunity to walk through the calibrated volume to become accustomed to the equipment. With the targets in place, the subjects stood on the force plate to normalize force plate data relative to their body weight. The subjects were then asked to walk barefoot through the calibrated volume. Subjects were required to strike the first force plate with their entire targeted foot and contact the second force plate at initial contact with that same foot in order to have a successful trial. Right trials were taken with the lower extremity targets on the right lower extremity. Left trials were taken with the lower extremity targets on the left lower extremity. Trunk targets were not removed between right and left sided trials. A total of six successful walking trials were recorded per lower extremity for each subject (twelve trials). EMG data were collected after the walking trials were completed so EMG equipment would not interfere with an individual's normal gait. Following the walking trials, subjects were asked to stand in the working volume so a standing file could be recorded. The standing file is used to identify additional target locations (medial condyle and medial and lateral malleoli) and to calculate those targets' position relative to their adjacent dynamic local coordinate systems. Additionally, knee and ankle joint centers are calculated using the standing file data. The hip joint center is calculated using methods described by Seidel, Marchinda, and Soutas-Little (1993). Dynamic and standing file target locations and calculated joint centers relative to dynamic local coordinate systems are used to calculate local coordinate systems which are aligned with the body segments. Adjacent local coordinate systems are used to define angular relationships between body segments. For the trunk, the local coordinate system is used to describe motions of the trunk relative to the pelvis and relative to the laboratory coordinate system. Pelvic orientation is described relative to the laboratory coordinate system. To eliminate inter-rater error, the clinical examination, targeting, and data collection were performed by a consistent researcher for all subjects.

Data

Processing

Following data collection, further processing was necessary to convert the data into meaningful forms, such as a graph representing trunk kinematic angles. Three-dimensional target coordinates were determined through DLT by combining two cameras' two-dimensional target position vectors; a process called tracking. Tracking involved identification, by a researcher, of all corresponding targets from at least two different cameras, for calculation of three-dimensional data. Following tracking, a linear interpolation algorithm was used to substitute missing data points if targets were momentarily obstructed. Foot targets were most frequently obstructed due to the swing of the contralateral extremity interfering with a camera's view of targets. Trunk and pelvic targets were not frequently obstructed. Therefore, most interpolation was performed with foot and ankle data. Data from all subject trials included in this study were interpolated over no more than twenty frames. Twenty frames corresponded to approximately .2 seconds worth of data or one-fifth of the gait cycle. The three-dimensional position data were low-pass filtered in the frequency domain with a batch-adaptive linear phase filtering procedure developed by D'Amico and Ferrigno (1990). This is an autoregressive model which selects the filter band-width and the filter shape by assessing the target coordinates within the signal and noise spectrum. Data were then converted into a standard computer language format (ASCII) for use in lab developed computer processing software. To process kinematic data, local coordinate systems aligned with the trunk and pelvis were calculated. The local coordinate systems were aligned with these segments using three non-colinear targets attached to the respective body segments. Two target positions were used to first create an anatomical axis, while the third target made up an anatomical plane. For the trunk, the sternal notch and T_4 targets were used to create the anatomical axis, while the T_9 target made up the plane. At the pelvis, left and right ASIS targets formed the axis, while the S_2 target made up the anatomical plane. The orientation of the trunk local coordinate system was described relative to both the local pelvic and global laboratory coordinate systems using a joint coordinate system. The joint coordinate system is a non-orthogonal system (not mutually perpendicular) fixed to a joint and was developed by Grood and Suntay (1983). The joint coordinate system was used to determine the orientation of one segment relative to another, described as joint angles. Trunk kinematic data in each of the cardinal planes (sagittal, frontal, and transverse) was plotted in degrees of motion versus percentage of gait cycle.

Statistical Analysis

Descriptive statistics including mean and standard deviation calculations were performed on the kinematic and demographic data. Six trials of kinematic data per subject were averaged to represent the mean intra-subject trunk kinematics in each of the cardinal planes. For one subject, only four trials were used to develop mean trunk kinematics due to difficulties with data tracking. These four trials did not require greater than twenty frames of interpolation. In order to determine the mean inter-subject trunk kinematics in each of the cardinal planes, all of the mean intra-subject kinematic files were compiled and an ensemble average was calculated at each one percent of the gait cycle. We expected trials between and within subjects would not consistently occur within the same interval (i.e. trial 1 occurs over the interval from 1 - 800 ms while trial 2 occurs over the interval 1-900 ms) due to variability within an individual's walking pattern. As a result, each sample could have been associated with a different percentage of the gait cycle. Using the method of cubic splining, each trial graph was defined by a polynomial equation to normalize the data points to each percentage of the gait cycle. This allowed for comparison between two separate trials and was essential for calculating the ensemble average.

Smith (1993) indicated that a subject's walking pattern varied between repeated trials. In order to best represent a normative kinematic database, the amount of intra- and inter- subject variability was assessed. Therefore, a coefficient of variation (CV), as described by Winter (1987), was used to determine the variance in motion for each one percentage of the gait cycle. This CV can best be described as a variability to signal ratio. This means that the amount of variability about the ensemble average is divided by the mean value of a trunk kinematic data point at each percentage of the gait cycle. CV is expressed as a percentage of variability. A CV was calculated for each subject to determine the amount of stride variation between his/her six trials (intra-subject variation). A CV was also calculated on group data to determine the amount of stride variation between subjects (inter-subject variation). Group CV was calculated by using all trials (100). The equation for CV was as follows:

$$CV = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\sigma_i^2}}{\frac{1}{n}\sum_{i=1}^{n}|X_i|}$$

where:

n was the number of intervals analyzed (in this study, n = 100, as each percentage of the gait cycle represented one interval)

X_i was the mean value of the kinematic data points, at each i^{th} interval, for all trials

σ_i was the standard deviation from the mean value of the kinematic data points, at each i^{th} interval, for all trials

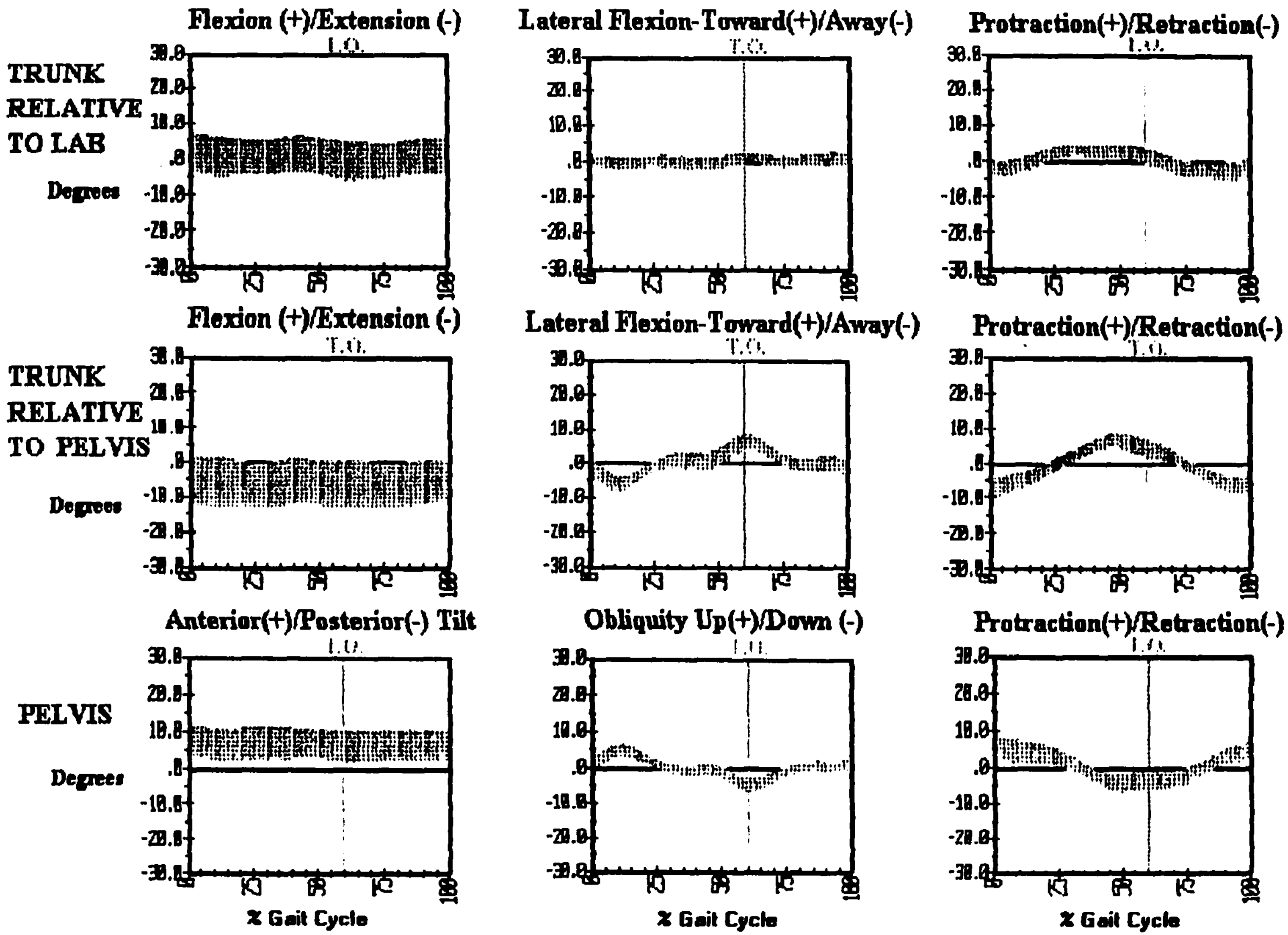
CHAPTER FOUR

RESULTS

Normal range of trunk rotations in the three cardinal planes relative to the lab and the pelvis will be presented. Subjects ambulated with an average velocity of 1.36 m/s ± .18 m/s. Graph 4.1 is provided to allow for comparison of all trunk and pelvic motions. Additionally, trunk motion will be qualitatively described relative to each subphase of the gait cycle. Quantitative descriptions of trunk motion including mean, standard deviation, and intra- and inter-subject coefficient of variation will also be presented. A larger intra-subject coefficient of variation was found for combined right and left trials, than for trials on the left or the right alone. This variation between right and left trials differs from that found by Sutherland, Olshen, Biden, & Wyatt in 1989. Equal numbers of right and left trials (3 of each) were taken from each subject to calculate ensemble averages in order to accommodate these intra-subject variations. For the purpose of this study, ensemble averages will be presented using right and left trials combined. Due to processing difficulties, only four total trials (two per side) were analyzed for one of the subjects and two subjects were dropped from the study.

Demographics

Seventeen normal subjects (11 females and 6 males) voluntarily participated in this study. Subjects ranged in age from 21 - 47, with an average age of 28 ± 7 years. All subjects were free of spinal deformity and dysfunction and were screened for neurological and musculoskeletal abnormalities. Patients not meeting requirements for normal were



Graph 4.1 Summary of Normative Trunk and Pelvic Angles

eliminated from the study. For a summary of descriptive demographic data see Table 4.1.

Trunk displacements in the three cardinal planes

Sagittal plane

Sagittal plane angles ranged from 1.97 ± 4.76 degrees of flexion to .65 ± 4.23 degrees of extension for trunk relative to lab. However, sagittal plane angles for trunk relative to pelvis had a mean range of 5.34 ± 6.15 degrees of extension to 6.95 ± 5.60 degrees of extension. Finally, angles in the sagittal plane for pelvic tilt ranged from 7.52 ± 3.24 degrees of anterior tilt to 5.93 ± 3.62 degrees of anterior tilt.

Frontal plane

Frontal plane angles for trunk relative to the lab ranged from 1.03 ± .97 degrees of lateral flexion away from the stance limb to .68 ± 1.01 degrees of lateral flexion toward the stance limb. Angles for trunk relative to pelvis had a mean range of 5.96 ± 1.6 degrees of lateral flexion toward the stance limb to 6.16 ± 1.73 degrees of lateral flexion away from the stance limb. Frontal plane angles for the pelvis relative to the lab had a mean range of 4.86 ± 1.09 degrees of right pelvic obliquity to 4.80 ± 1.19 degrees of left pelvic obliquity.

Transverse plane

Transverse plane rotations for trunk relative to the lab ranged from 2.79 ± .82 degrees of protraction to 2.83 ± 1.42 degrees of retraction. Rotation in the transverse plane for trunk relative to pelvis had a mean displacement range of 7.53 ± 2.14 degrees of retraction to 6.40 ± 1.53 degrees of protraction. Angles for pelvis relative to lab in the

Subject	Age	Gender	Height (in)	Weight (lbs.)
DM1	27	m	71.5	153.81
KD2	26	f	67.0	156.54
TC3	23	f	63.0	130.73
BH5	31	m	68.0	182.77
KS6	24	f	64.5	119.97
SA7	42	f	68.0	163.32
BS8	23	f	63.0	133.79
BW9	23	f	68.0	118.32
TA10	32	f	65.0	125.49
MJ11	29	f	65.0	134.63
TM12	25	f	66.0	152.11
AD13	22	f	69.0	147.41
MA14	21	m	69.0	179.33
CE15	47	f	67.5	148.32
CS17	26	m	67.5	126.93
KA18	25	m	72.5	178.16
RC19	30	m	71.0	172.08
Average	28		67.4	148.45
Std Dev.	7.0	m = 5	2.8	21.41
		f = 12		

Table 4.1 Subject Demographics

transverse plane had mean range from 5.38 ± 2.48 degrees of counterclockwise rotation to 4.24 ± 1.73 degrees of clockwise rotation.

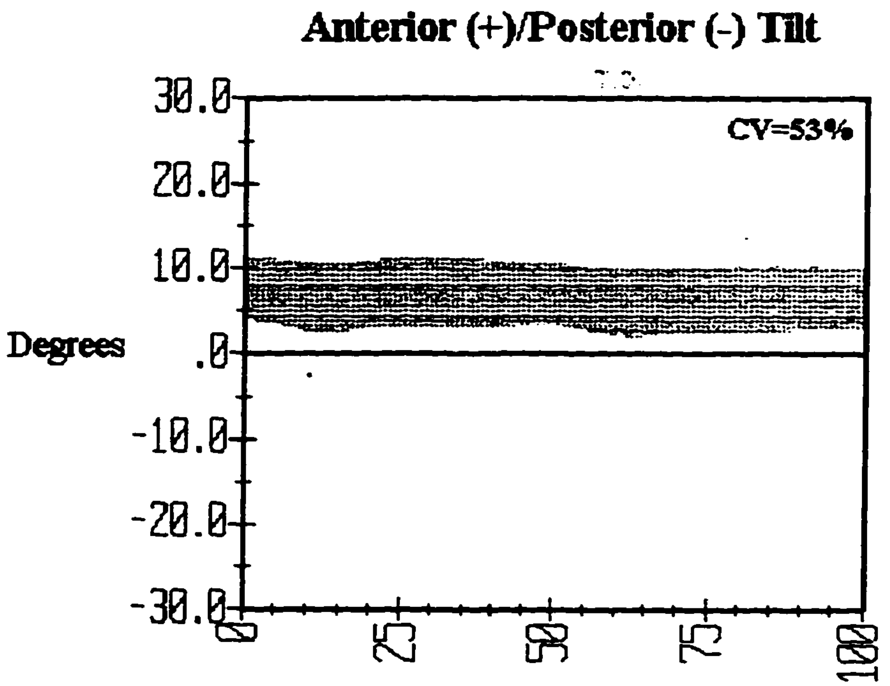
Trunk movement during the subphases of gait

Sagittal plane

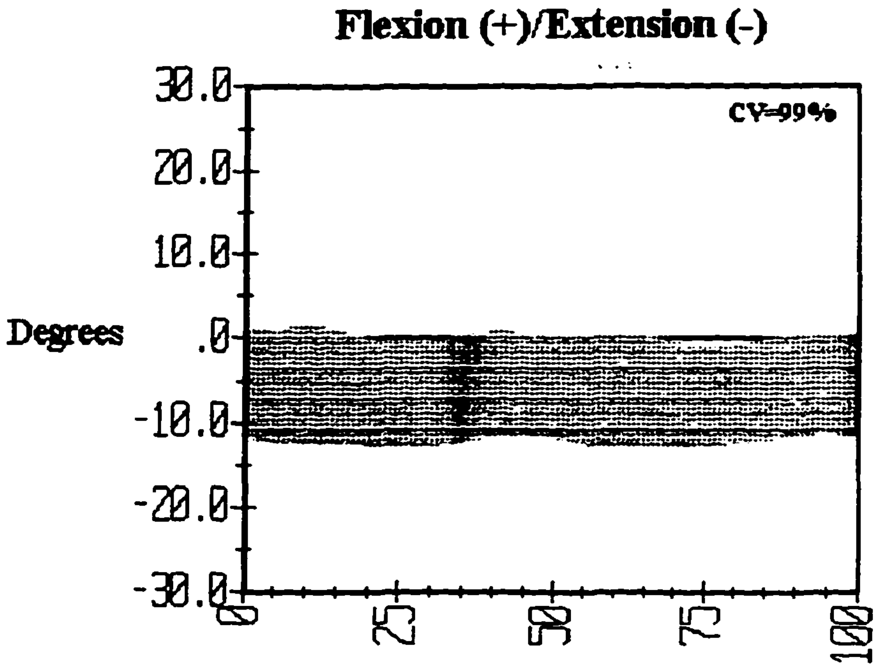
Mean pelvic tilt at initial contact/loading response (0-10% of the gait cycle) was 7.52 ± 3.24 degrees of anterior tilt. The pelvis remained in approximately the same amount of pelvic tilt throughout the gait cycle (see Graph 4.2). Mean trunk sagittal plane movement relative to the pelvis was also consistent through the gait cycle starting with 5.34 ± 4.53 degrees of extension at initial contact (see Graph 4.3). Two small oscillations into extension occurred, one at the end of midstance (26%) and one during midswing (76%). These oscillations had a peak mean value of 6.71 ± 5.8 and 6.95 ± 5.59 degrees of extension, respectively. Trunk values relative to the lab showed a similar trend of dual oscillations (see Graph 4.4). These oscillations occurred at end of midstance (26%) and during midswing (73%) with peak mean values of .28 ± 3.61 and .65 ± 4.17 degrees of extension, respectively.

Frontal Plane

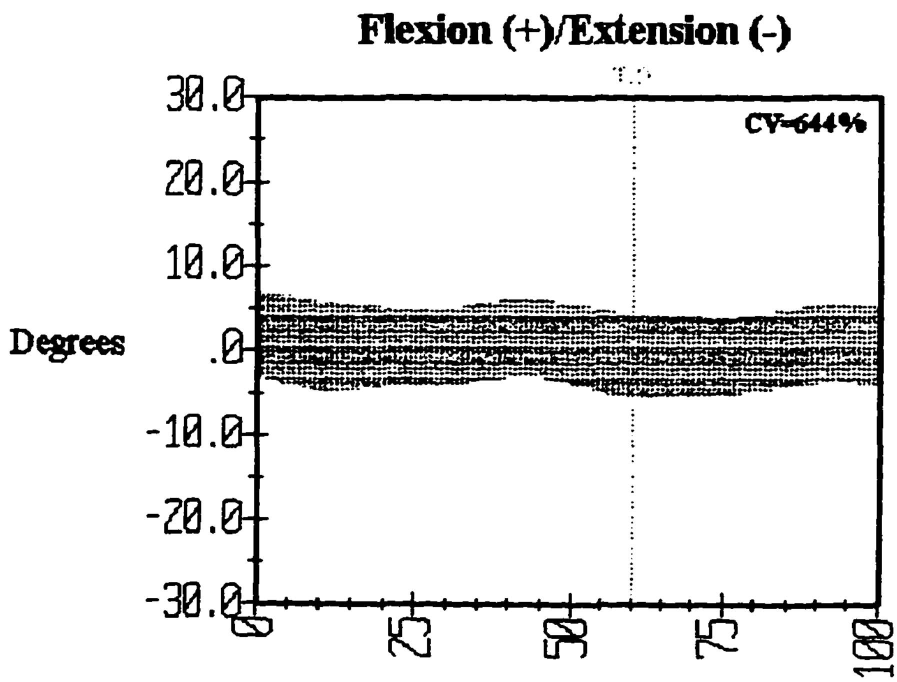
Pelvic position in the frontal plane at initial contact was relatively neutral at 1.17 ± 1.23 degrees of upward obliquity (see Graph 4.5). There was an upward progression of the stance side of the pelvis through loading response, when it reached a maximum of 4.86 ± 1.09 degrees at 12% of the gait cycle. The pelvic motion returned to neutral at late midstance (29%) and continued in a neutral position until terminal stance (48%). Motion then progressed in a downward obliquity with an inferior peak at initial swing (62%). The



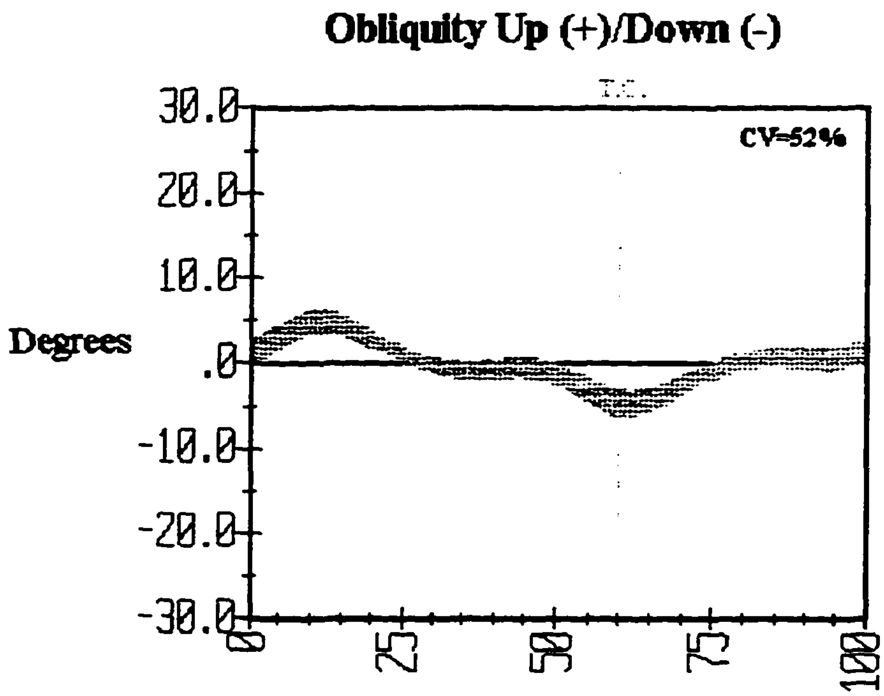
Graph 4.2 Pelvic Tilt - Sagittal Plane



Graph 4.3 Trunk Relative to Pelvis - Sagittal Plane



Graph 4.4 Trunk Relative to Lab - Sagittal Plane



Graph 4.5 Pelvic Obliquity - Frontal Plane

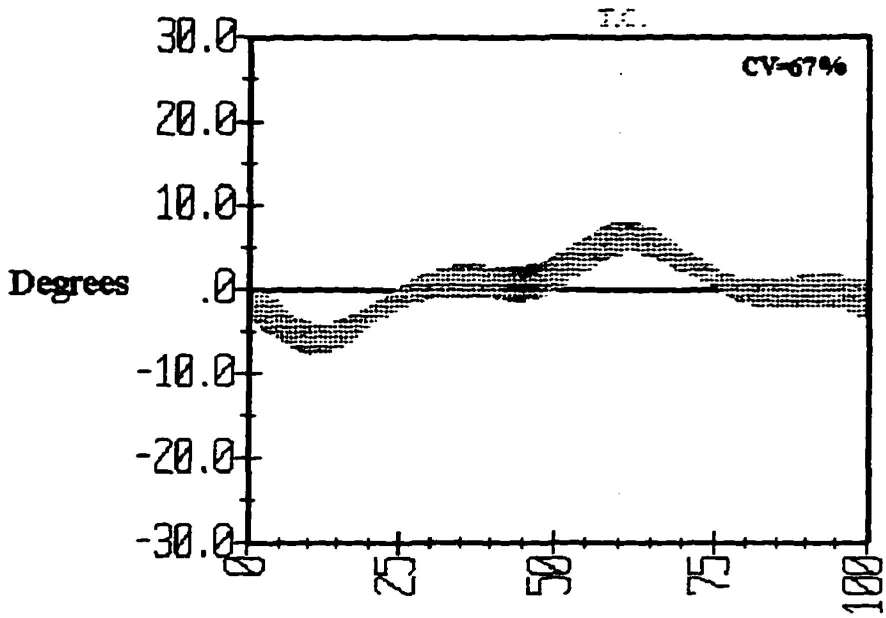
mean value of maximum downward obliquity was 4.80 ± 1.19 degrees. The pelvis returned to neutral during midswing (79%) and remained so until the second initial contact.

Relative to the pelvis, the trunk at initial contact was positioned in 1.49 ± 1.14 degrees of lateral flexion toward the stance limb (see Graph 4.6). The trunk continued to laterally flex until midstance (12%), with a mean peak excursion over the stance limb of 5.96 ± 1.6 degrees. Trunk motion returned to neutral at late midstance (26%) and remained in a neutral position until terminal stance (48%). The trunk then moved away from the stance limb at pre-swing and peaked away from the reference limb at midswing (62%) with mean value 6.16 ± 1.67 degrees of lateral flexion. Movement of the trunk away from the swinging reference limb during pre-swing corresponded to trunk movement toward the contralateral limb which was beginning to contact the ground. The trunk returned to neutral during midswing (76%) and remained neutral until the second initial contact. Relative to the lab, the mean trunk displacement fluctuated only 1.7 degrees about neutral throughout the gait cycle (see Graph 4.7).

Transverse Plane

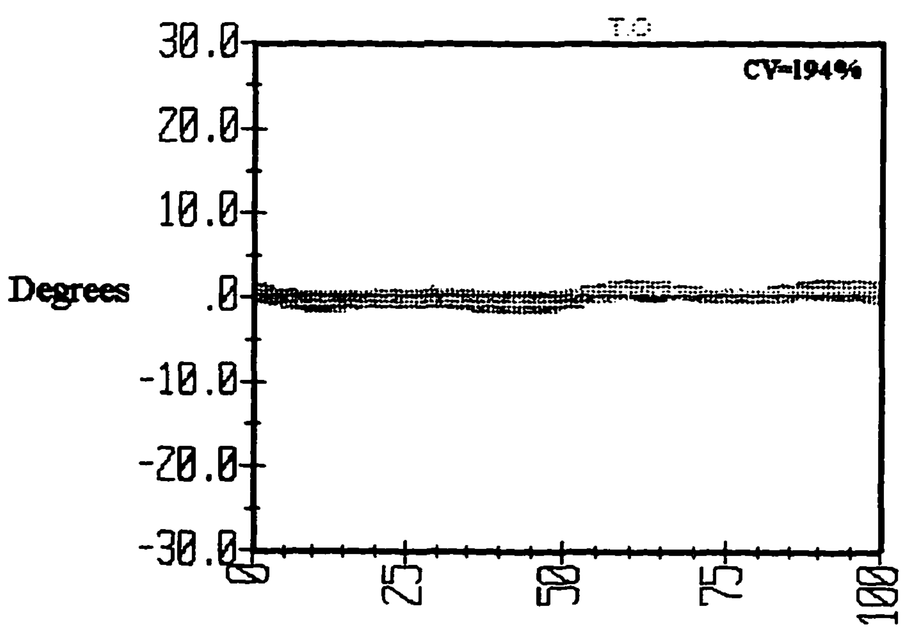
The pelvis began the gait cycle in 5.38 ± 2.49 degrees of protraction (see Graph 4.8). Gradual pelvic retraction occurred immediately, putting the pelvis in neutral at midstance (30%). The pelvis reached peak retraction of 4.24 ± 1.73 degrees at terminal stance (50%). The pelvis remained in retraction into midswing (72%) until it reversed direction, where it was protracted through the remainder of the swing phase.

Lateral Flexion - Toward (+)/Away (-) from Reference Limb

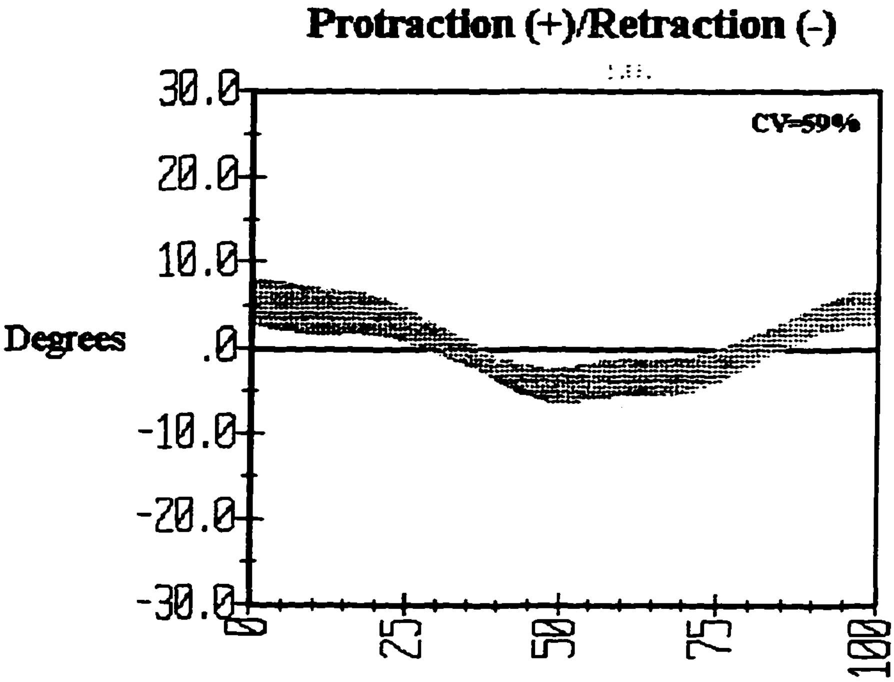


Graph 4.6 Trunk Relative to Pelvis - Frontal Plane

Lateral Flexion - Toward (+)/Away (-) from Reference Limb



Graph 4.7 Trunk Relative to Lab - Frontal Plane



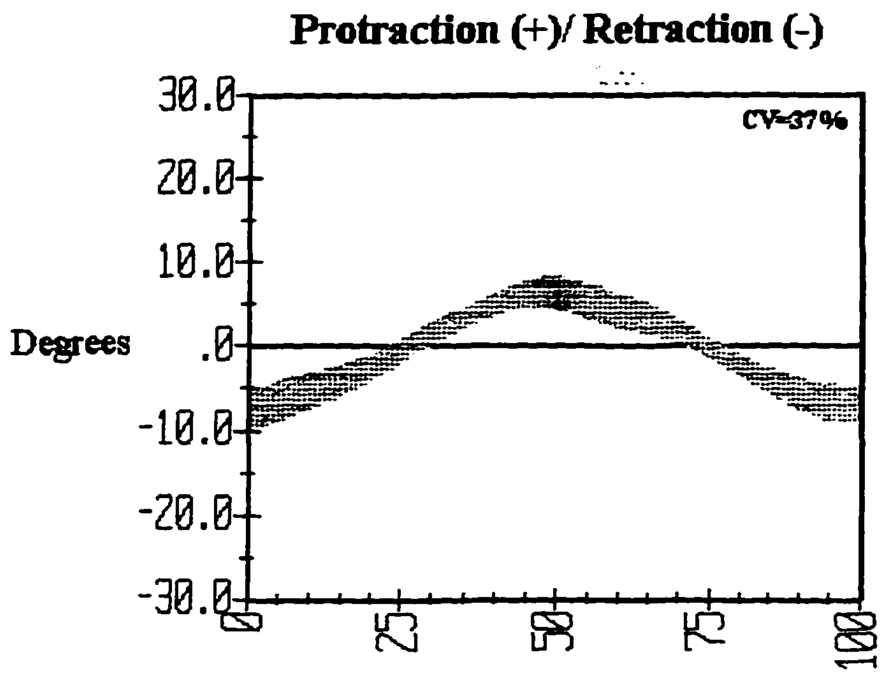
Graph 4.8 Pelvic Rotation - Transverse Plane

The trunk relative to the pelvis, was at 7.53 ± 2.14 degrees of retraction at initial contact (see Graph 4.9). Following initial contact, the trunk relative to the pelvis moved into protraction and reached a peak mean value of 6.40 ± 1.53 degrees of protraction in terminal stance (48%). From this peak protraction, the motion reversed and progressed to 6.85 ± 1.98 degrees of peak retraction by late terminal swing (98%).

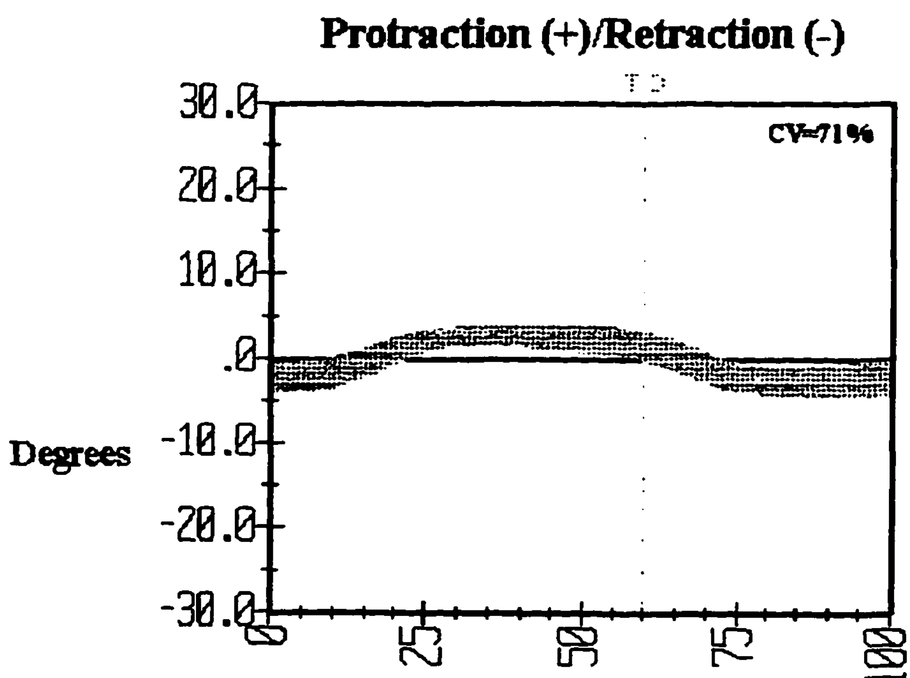
The trunk relative to the lab began in 2.32 ± 1.59 degrees of retraction and progressed to 2.79 ± .82 of protraction at terminal stance (35%) (see Graph 4.10). Gradually, the rotation reversed and progressed to a peak mean retraction value of 2.83 ± 1.45 degrees. This retraction remained throughout the rest of the swing phase.

Coefficient of Variation

Intra-subject coefficient of variation (CV) was calculated to determine the amount of stride variability in an individual's gait pattern. An inter-subject CV was also calculated to determine the amount of stride-to-stride variability between subjects. Subjects had low stride variability in trunk kinematics. A low intra-subject coefficient of variation was found in pelvic movements in all three planes, while the highest stride variability within subjects was found in movements of the trunk relative to the pelvis. There was a high degree of stride variability between subjects. The greatest amount of inter-subject variability occurred in the sagittal plane and the least amount of variability occurred in the frontal plane. See Tables 4.2 and 4.3 for values of intra- and inter-subject variation. Additionally, the inter-subject coefficient of variation can be found in the upper right hand corner of graphs 4.2 through 4.10.



Graph 4.9 Trunk Relative to Pelvis - Transverse Plane



Graph 4.10 Trunk Relative to Lab - Transverse Plane

	Sagittal	Frontal	Transverse
Trunk Relative to Lab	52%	69%	76%
Trunk Relative to Pelvis	80%	182%	170%
Pelvis	28%	55%	82%

Table 4.2 Intra-subject coefficients of variation

	Sagittal	Frontal	Transverse
Trunk Relative to Lab	644%	194%	71%
Trunk Relative to Pelvis	99%	67%	37%
Pelvis	53%	52%	59%

Table 4.3 Inter-subject coefficients of variation

CHAPTER 5

DISCUSSION

There was a distinct pattern of kinematics in the pelvis and trunk during gait in the normal subjects tested within this study. In the sagittal plane, relatively small amounts of movement were found in the pelvis compared to the trunk, which is consistent with findings of Cappozzo's 1981 study. The trunk, in the sagittal plane, was extended through the gait cycle but exhibited two small peak oscillations in extension at the end of mid-stance and during mid-swing (single support phases). These oscillations ranged from 5.34 to 6.95 degrees of extension. Past researchers also found two consistent peaks of extension oscillations which ranged between two and ten degrees (Thorstensson et al., 1982, Krebs et al., 1992, and Crosbie et al., 1997a). The researchers in the present study noted that trunk movement relative to the lab fluctuated near neutral, while trunk movement relative to the pelvis remained near five degrees of extension. An anteriorly tilted pelvis would predispose the trunk relative to the pelvis to be in an extended position throughout the gait cycle. An anterior tilt was found in the pelvis, throughout the gait cycle, in this present study (see Graph 4.1). Other researchers have reported that the pelvis was in an anteriorly tilted position throughout the gait cycle (Murray et al., 1967 and Perry, 1992) Conversely, Crosbie et al. (1997a) found different patterns of trunk and pelvic movement during ambulation, however, the targeting protocol that they used was different than that which was used in this present study. Additionally, no clear description of joint angle calculations were provided by Crosbie et al. (1997a). Crosbie et al. also reported a difference in where trunk and pelvis movements occurred in the range, as compared to this present study. Other researchers found patterns of trunk and pelvic movements similar to those reported in this study (Thorstensson et al., 1982 and Krebs et al., 1992), however, these patterns differed in where they occurred in the range. Most researchers found the trunk remained in a neutral or slightly flexed position (Thurston, and Harris, 1983, Opila-Correia, 1990, and Krebs et al., 1992) while the trunk movements recorded in this present study remained in approximately five degrees of extension. It is possible that anterior tilt and trunk extension positions within the range are representative of the targeting protocol used in this study and variations in subject body types.

A high variation about the mean (standard deviation), in all sagittal plane movements, was reported when compared to the frontal and transverse planes. Spinal targets were placed at the tip of the spinous process. Subjects variability in spinous processes length and shape, and interspinous ligament density may have contributed to a greater error in reliability of target placement. Finally, there may be normal anatomical and functional variations which also contribute to larger normative bands of movement in the sagittal plane. For instance, during targeting researchers noted that subjects varied in their anatomical position of T_4 spinous process. In some subjects, the spinous process of T_4 was superior or inferior to the sternal notch. Functional variations between subjects were noted observationally. For example, some subjects seemed to walk with a more extended trunk, while others were in a more neutral position.

Frontal plane motion was determined in this study to have a consistent pattern of trunk and pelvic movement. These patterns were nearly out of phase when comparing the pelvic motion to trunk motion relative to the pelvis (see Graphs 4.6 and 4.7). Movements of the trunk relative to the lab showed marked decreases in amplitude compared to trunk motion relative to the pelvis. In the present study, a pattern of peak lateral flexion of the trunk toward the stance limb occurred at loading response, and peak lateral flexion occurred away from the stance limb occurred at toe-off. Toe-off for the reference limb corresponded to loading response of the contralateral limb. The patterns of trunk rotation in the frontal plane reported in this present study were similar to those of Murray et al. (1964), Waters et al. (1973), Thorstensson et al. (1982), Krebs et al. (1992), and Crosbie et al.(1997a). However, Murray et al. (1964) found that peak lateral flexion toward the stance limb occurred at midstance, whereas Thorstensson et al. (1982) reported peak flexion toward the stance limb at initial contact. The researchers in this present study suggest that initial contact is an instantaneous component of loading response, therefore, the results for trunk lateral flexion are quite similar. Opila-Correia (1990) denied any significant patterns of trunk movement in the frontal plane, which conflicted with results of this present study and those of past researchers.

In the transverse plane, this study supports past research that the pelvis and trunk move in opposite directions relative to each other during the gait cycle. (Gregerson & Lucas, 1967, Chapman and Kurokawa, 1969, Krebs et al., 1992, and Crosbie et al., 1997a). Maximal rotation of the trunk toward the referenced limb occurred at initial contact while maximal rotation away from the referenced limb occurred during terminal stance, just prior to toe-off. These trunk motions were found to be opposite of the movements occurring in the pelvis. Maximal excursions for the trunk and pelvis only varied by 2 % of the gait cycle, with trunk rotation proceeding pelvic rotation. Chapman and Kurokawa (1969), found that counter-rotation occurred and the opposite rotations between the shoulders and pelvis were not simultaneous. Chapman and Kurokawa (1969) indicated that this "out of phase" relationship may be due to upper trunk movement occurring as a passive response to the rotation of the pelvis. Ongoing EMG study of trunk muscles and arm swing may help to explain the relationship between trunk and pelvic movement in the transverse plane.

The researchers in the present study noted a trend of less excursion of the trunk relative to the lab compared to the trunk relative to the pelvis or the pelvis alone. This data could support the theory that the trunk is a dampener of ground reaction forces as proposed by Chapman and Kurokawa (1969), Waters and Morris (1972), and Townsend (1981). This dampening affect is thought to be a component of stabilization of the head and eyes during gait and a reduction of forces on the central nervous system. The dampening of trunk and pelvic motions may also minimize large shifts in center of mass. Decreasing the excursion of the center of mass minimizes energy expended during walking. An example from this study would be that as the pelvis shifted upward during loading response, the trunk laterally flexed over the stance limb, which minimized the horizontal excursion of the center of mass. Crosbie et al. (1997a) hypothesized that lateral flexion toward the swing limb reduced the excursion of the center of mass, thereby, conserving energy during ambulation. However, his data did not support this hypothesis.

Although the present research has shown support for the theoretical dampening function of the trunk during gait, there was also support for Gracovetsky's (1988) theory of the spinal engine. If Gracovetsky were correct, then one would expect to see lateral flexion of the trunk occurring immediately prior to opposite rotation of the pelvis. This motion should be particularly obvious prior to the pelvis protracting to advance the limb in swing. There was evidence of lateral flexion and opposite rotation in the trunk prior to pelvic protraction in this study. A sharp rise in lateral flexion occurred away from the referenced limb just prior to the initiation of pelvic protraction in swing. According to neutral spine mechanics, lateral flexion and rotation should occur simultaneously (Fryette, 1954). However, these opposite trunk and pelvic motions did not occur simultaneously. Therefore, other structures such as the posterior ligaments and fascia must have contributed to the movements seen. Further support for Gracovetsky's theory can be found in the rotation/counter-rotation motion which occurred between the trunk and pelvis. According to Gracovetsky, efficient gait is accomplished through the loading of the passive elastic component of the posterior ligaments of the spine with transfer of energy to the lower limbs. In the present study, the counter-rotation of the trunk on the pelvis could act in a coiling manner to load the passive elastic component of the posterior ligaments and fascia of the spine. If the counter-rotation loads the passive elastic component of the posterior ligaments of the spine, as Gracovetsky theorized, the loading would play an instrumental role in the transference of energy to the pelvis and lower extremities to fuel gait. Although support for both Gracovetsky's and dampening theories of trunk function during gait can be found in this present study, the actual function of the trunk during gait cannot be determined by data from this research alone. Kinetic and kinematic data along with trunk EMG are needed to progress theories on trunk function during gait.

When the results of this present study were analyzed, the researchers noted a relatively large difference in the intra-subject coefficient of variation when combining right and left trials as opposed to trials taken only on the left or only on the right. The difference between right and left trials may be due to a subject's comfort level. Data collection for each subject took approximately 2-3 hours. This time would allow a subject to become more familiar with the targeting protocol and lab environment as the test proceeded. The subject may have altered his/her gait pattern throughout the course of data collection. Right trials were consistently taken first, therefore, the subject may not have been as comfortable at this time and could have had a bearing on their gait pattern.

Inter-subject coefficient of variation was found to be relatively higher for the trunk relative to lab versus the trunk relative to the pelvis and pelvis alone, in all planes. This increased CV could be explained by the normal postural variations between subjects, targeting protocol, or intra-subject variation in spinal and lower extremity range of motion. As the CV is a ratio of variability about the mean to the mean kinematic data points, small means with a corresponding large standard deviations will contribute to a large CV. For example, in the sagittal plane for motion of the trunk relative to the lab, the inter-subject coefficient of variation was 644%. Mean sagittal plane trunk motion relative to the lab was approximately $.65 \pm 4.23$ degrees. In transverse plane trunk motion relative to the lab, the CV was 71%, with a mean of 6.40 ± 1.53. Past reports of CV have been focused on the lower extremities or the lower thoracic, lumbar, and pelvic regions

(Winter, 1991 and Crosbie et al., 1997b). There have not been reports of trunk coefficients of variations, therefore, comparisons to this study cannot be made.

Limitations

This was a preliminary study to develop a normal database for the West Michigan area and specifically the Mary Free Bed/ Grand Valley State University Center for Human Kinetic Studies. Some variables that were not controlled included age, gender, and walking speed. Past research has shown that these variables, except gender, may affect trunk motion during gait (Murray et al., 1964; Chapman & Kurokawa, 1969; Waters et al., 1973; Cappozzo, 1981; and Crosbie et al., 1997). Due to the lack of research on gender kinematic differences, concluding that gender has an affect on gait patterns is premature. Gender has been included in the limitations as it was not a controlled variable. Methodology limitations included use of a sample of convenience, small sample size, and targeting protocol.

Sources of Error

Systematic sources of error inherent in the Elite camera system and other equipment could not be controlled. Andriacchi (1985) indicated that any optoelectronic system has inherent difficulties in target detection and processing which can contribute to error. The researchers in the present study attempted to account for these difficulties by using larger sized targets which enhanced detection of the infra-red signal and optimized reflection. The targeting protocol was developed specifically for use in this study and has only been tested in a pilot study. Random error was introduced by variation in postural alignment, such as horizontal alignment of the sternal notch and T_4 targets. This variation in horizontal alignment resulted in relative extension found in the trunk in the sagittal plane. Targets were placed over bony landmarks, on the skin. Although skin mounted targets could be susceptible to varying degrees of movement during gait, Thorstensson et al.(1984) has shown that movement of targets due to skin movement is less than 2 mm. Finally, one researcher consistently targeted all subjects in this study, but determination of bony landmarks is subjective and dependent on reliable palpation skills.

Future research

Future research should include a larger sample size to further expand this preliminary database of normal trunk kinematics. Secondly, the targeting protocol could be altered by visually aligning the sternal notch target and the superior posterior trunk target versus direct placement on T_4. This change in targeting protocol may eliminate the relative trunk extension seen in the sagittal plane. The EMG, gait parameters, anthropometric measurements, and lower extremity kinematic data collected during this study could be used in future research to better understand the function of the trunk in gait. Additional variables to be included in future gait research are gender, arm-swing, and an analysis of the different regions of the trunk (i.e. cervical, thoracic, and lumbar). Development of a common valid protocol would be helpful to compare these results to those from other centers. Finally, test-retest reliability, intra- and inter-rater reliability testing would be useful to clinicians and researchers. This data would provide practical information on the movements of the trunk during gait, over time.

Clinical Implications

The present researchers have developed a preliminary database of normal trunk kinematics during gait. The area of most effective use of this database is through the Mary Free Bed/ Grand Valley State University Center for Human Kinetic Studies to aid in analysis of pathological gait in adults. Other gait analysis laboratories who use the Elite cameras, comparable processing software, and the described testing procedure may also utilize this database for comparison. Clinicians can compare this normative data to their patient's gait pattern to determine if pathologies in the trunk exist. The present study can be added to the short list of others regarding trunk movement during gait, to begin to postulate on the trunk's function during gait.

Conclusion

The purpose of this study on normal trunk kinematics during gait was to establish a preliminary normative database for comparison to pathological gait. Future research which incorporates trunk kinematic information with trunk kinetics, EMG, detailed trunk segmental analysis, and arm swing kinematics will provide a more comprehensive understanding of the function of the trunk during gait. Knowledge of trunk function can guide clinicians in assessment and treatment of patients with pathological conditions which affect gait.

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APPENDIX A

THE MARY FREE BED & GRAND VALLEY STATE UNIVERSITY CENTER FOR HUMAN KINETICS STUDIES

Dear Participants,

The Mary Free Bed and Grand Valley State University Center for Human Kinetic Studies has been designed to analyze the walking patterns of individuals. Clinically, the lab analyzes movement problems associated with neuromuscular disorders; specifically the walking patterns of children with cerebral palsy. The lab uses highly technical, non-invasive equipment for its biomechanical evaluations.

The purpose of our study is to evaluate how the normal adult's trunk moves during walking. These walking patterns will be used for comparison in analysis of pathologic gait and future research.

This study is being conducted as a master's thesis by graduate physical therapy students at Grand Valley State University and will be supervised by a licensed physical therapist.

Your Appointment at the Human Kinetics Lab is Scheduled for:

DATE ________________ TIME ________________

What to Bring:

You will be required to wear "speedo"-like shorts and a top which will reveal the breastbone and upper spine between the shoulder blades. This is to enable cameras to clearly see the markers which will be placed on the skin.

Testing Procedures:

1) Gait analysis tests normally take 2-3 hours. Because of this, formal breaks will be provided throughout the test.

2) Upon arrival, you will be asked to fill out a questionnaire regarding your past medical history.

3) Following the questionnaire, you will be required to change into the testing apparel so that a graduate physical therapy student can perform a clinical examination. This

clinical examination will determine participation criteria and will be supervised by a licensed physical therapist.

4) If you meet the participation criteria, you will be prepared for data collection:
   a) small tape-covered plastic spheres will be placed on your legs and trunk
   b) eight small areas will be shaved, cleansed, and marked using muscle activity sensors

5) You will be asked to walk across the lab several times while videocameras record your movements

Thank you for volunteering your time and interest to this project. Enclosed is a brochure regarding additional information about the lab and directions. For further information, please contact:

Lisa Elders, Heather Greenwald, or Celeste Sartor
Suite 101, 2020 Raybrook SE
Grand Rapids, MI 49546
(616) 954-2318

Sincerely,

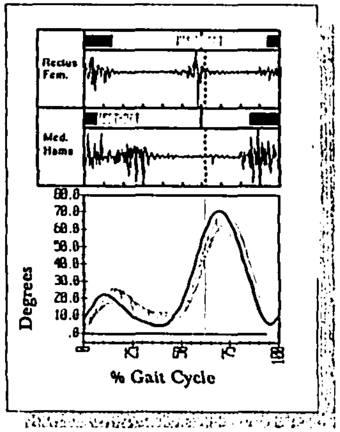
Lisa Elders, SPT
Heather Greenwald, SPT
Celeste Sartor, SPT

Results

Test results are sent to the referring physician within approximately three weeks.

Payment

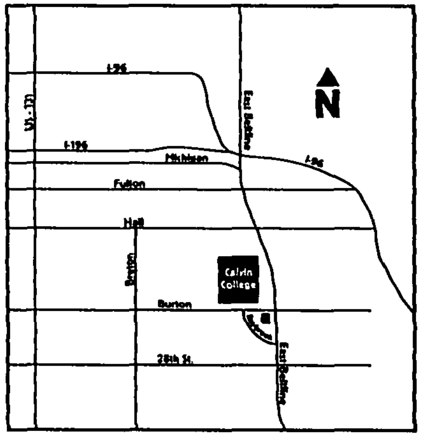
Testing charges depend upon the complexity of the specific evaluation requested. Mary Free Bed Hospital and Rehabilitation Center works with patients and their insurance companies to make satisfactory payment arrangements.



Dynamic electromyography of the thigh muscles and knee flexion/extension angles during walking.

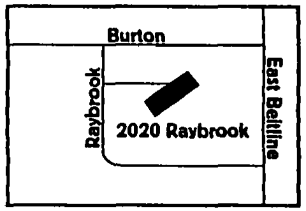
Location

2020 Raybrook SE,
located South of Burton Ave, just West of the East Beltline (M 37).



Detail

Parking in front of bldg. Suite 101, CHKS, is on the lower level.



For Further Information Contact:
Center for Human Kinetic Studies

2020 Raybrook SE, Suite 101
Grand Rapids, Michigan 49546
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E-Mail: kinetic@river.it.gvsu.edu

Support for the establishment of the Kinetics lab was provided by the Mary Free Bed Guild & Steelcase Foundation.

MARY FREE BED **Center for Human Kinetics Studies**

Gait Analysis

Mary Free Bed Hospital & Rehabilitation Center

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Grand Valley State University

APPENDIX B

The Function Of The Kinetics Lab

There are many individuals with neuromuscular impairments, such as cerebral palsy, who have difficulty walking. The Kinetics lab was established to assess walking ability. The lab uses high speed cameras, small spherical targets, muscle activity sensors and force platforms to record complex joint movements, muscle activity patterns and forces acting on the body during walking. This information is acquired and processed by computer. The referring physician is sent a written and graphical biomechanical summary. The evaluation is useful in establishing the most effective treatment program for patients with walking impairments.

Referral Procedure

Patients are accepted for a gait analysis by physician referral. Once the Kinetics lab receives a referral and other medical information from the physician the patient will be scheduled for a gait test.

What to Bring:

- Shorts or a bikini type bathing suit.
- Any orthotics, braces or assistive walking devices.
- The shoes normally worn by the patient.
- Any pertinent medical notes and/or physical therapy notes.
- Insurance information.
- A favorite snack, book, toy or other diversional activity to help pass the time during waiting periods.

Testing Procedure

- Upon arrival, the patient is asked to change into shorts or a bikini type bathing suit.
- A physical therapist performs an examination to measure the patient's joint range of motion and muscle strength.
- Small spherical targets and muscle activity sensors are placed on the patient using tape and straps.
- During walking, data are collected on force, motion and muscle activity.
- Testing takes approximately 3-4 hours depending upon the complexity of the test.

APPENDIX C

CENTER FOR HUMAN KINETIC STUDIES
HISTORY FORMAT

DATE:__________
SUBJECT INITIALS:_________________________ **AGE**_____

MEDICAL HISTORY: Describe past medical history including childhood illnesses, injuries such as sprains/strains, etc., and other diseases such as diabetes, heart disease, congenital deformities i.e.: club feet, dislocation, etc.)

1) Are you taking any prescriptions or over-the-counter medications? Yes No

If yes, list:

2) Have you had any X-rays, sonograms, computed tomography (CT) scans, bone scans, magnetic resonance imaging (MRI) done within the past year? Yes No

If yes, why? (please give results):

3)Have you ever had any surgeries? Yes No

If yes, list type and date:

4) Have you had any recent illnesses within the last 3 weeks (e.g. colds, influenza, infections, other)? Yes No

If yes, describe:

5) Have you had any injuries within the past six months which required medical attention/caused difficulty walking for over 24 hours? Yes No

If yes, describe:

6) Do you have any pain at the present time? Yes No

If yes, describe:

7) Check below if you have had a history of any of the following:

_____ scoliosis

_____ spinal surgery

_____ spodylolisthesis

_____ ankylosing spondylosis

_____ fractured vertebrae

_____ herniated disc

_____ neurological injury to the spinal cord and/or spinal nerves

7) Have you had any pain within the last 6 months? Yes No

If yes, describe:

APPENDIX D

Clinical Examination

Subject's Initials _________ Date______________

Posture (make comments on foot, ankle, knee, pelvis, and spine)

____

____

____

____ free of scoliosis
____ Leg Length Discrepancy < 6 mm

Screen:
Lower extremity

____	Squat		
____	Toe raises(S_1 & S_2)	____Right	____Left
____	Heel walking (L_4)		
____	Straight leg raise - to 70^0	____Right	____Left
____	Thomas Test	____Right	____Left
____	Ober Test	____Right	____Left
____	Manual Muscle Tests		
	Hip flexors(L_1 &L_2)	____Right	____Left
	Knee extensors (L_3)	____Right	____Left
	Great toe extensors(L_5)	____Right	____Left

Trunk
____ Forward flexion
____ Lateral flexion
____ Extension

SI joint
____ Standing forward flexion test is negative

Examiners Signature________________________________ Date______________

APPENDIX E

Clinical Examination Parameters and Exclusion Criteria

Clinical Examination Parameters:

Posture: Examiner is looking for moderate to severe deviations from normal posture. Specific attention will be paid to the alignment of the lower extremities and the spine.

Scoliosis: Determination of "free from scoliosis" will be made if there is no curve present in the spine in standing, and no rib hump is observable during standing forward flexion.

Leg Length: Leg Length will be determined by measuring from the inferior border of the ASIS to the inferior border of the medial malleolus.

Screening Procedures:

Squat: Is to be performed with patient using table or therapists arm for stabilization only. Heels must remain on the floor throughout the squat.

Toe Raises: Subject is to rise 10 consecutive times on his/her toes one foot at a time. The subject will be allowed to hang on to table or therapist for stabilization only.

Heel Walking: The subject is to walk 10 consecutive steps on his/her heels.

Straight Leg Raise: Performed per specifications of Kendall.

Thomas Test: Performed per specifications of Kendall.

Ober Test: Performed per specifications of Kendall.

Manual Muscles Testing: Subjects must score a 5/5 on all manual muscles tests as specified by Kendall.

Forward Flexion: The subject will bend forward and touch the superior medial malleolus using normal lumbopelvic rhythm. Normal lumbopelvic rhythm is described as a two-part movement involving both the spine and the pelvis. In the first 60 degrees, the pelvis remains fixed while the lumbar spine flexes. In the second phase, the gluteal muscles relax and the pelvis rotates about the femurs adding about another 25 degrees of flexion. Extension back to neutral is accomplished in the reverse order.

Lateral Flexion: Subject must be able to bend to the side (with no rotation) and touch the lateral condyle of the femur.

Extension: Subject must be able to obtain and maintain a prone on elbows position.

<u>Exclusion Criteria</u>:

Past Medical History:

Presence of pain and/or an orthopedic injury within the last six months which has limited normal walking is sufficient cause for subject exclusion from the study. Additionally, subjects will not be able to participate in the study if they have had a history of joint reconstructive surgery of the lower extremities, osteotomies, or those conditions listed under question seven of the appendix C. Subject report of radiographic or other imaging tests, medication use, and recent illness will be assessed on an individual basis, to determine whether they will affect gait or are representative of the exclusion criteria indicated above (i.e. MRI report of herniated disc).

Clinical Examination:

Presence of scoliosis, a leg length discrepancy of greater than six millimeters, and severe postural abnormalities are sufficient cause for subject exclusion from the study. Failure to satisfactorily meet three or more of the screening procedure criteria will also be cause for subject exclusion from the study.

APPENDIX F

INFORMED CONSENT

MARY FREE BED HOSPITAL AND REHABILITATION CENTER/ GRAND VALLEY STATE UNIVERSITY CENTER FOR HUMAN KINETIC STUDIES

A PRELIMINARY STUDY OF TRUNK KINEMATICS DURING WALKING IN NORMAL SUBJECTS

I understand that I am agreeing to participate in a research study designed to characterize parameters of walking, such as joint ranges of motion, forces exerted on the ground, and muscle activity during walking. I will allow the Center staff to place reflective markers on my skin. I understand that a Physical Therapy Student will ask about my past medical condition and perform a physical therapy evaluation on me. If my history and physical examination are not consistent with normative standards, I understand I may not be able to participate in this study.

I understand that during the test I will be wearing shorts and a top in order to expose the skin markers and sensors needed to collect data. I understand that I will be photographed and/or videotaped as part of the evaluation. The Center for Human Kinetic Studies (CHKS) will have custody of these data, but will only use the data for the purpose of analysis, education and/or reporting scientific results. I understand that my record will be kept confidential, as explained to and understood by me.

I understand that all of the procedures involved in this evaluation will take approximately four (4) hours, are non-invasive (nothing will penetrate my skin), and that the risks associated with normal walking, such as tripping or falling, are minimal. I understand that, in the unlikely event of minor injury, first aid will be provided, but further medical care will continue under the direction of my physician in accordance with my own particular financial arrangement.

The benefits of this test have been explained to me. They include assisting the CHKS in establishing data on non-impaired individuals and providing me with scientifically collected and interpreted data on my walking pattern.

I know that participation in this study is strictly on a volunteer basis and that I may withdraw my participation at any time. I understand that in no way would non-participation or withdrawal from this study affect treatment while at Mary Free Bed nor my educational status at GVSU. There will be no payment for my participation. I know that any questions I have, pertaining to this study, will be answered.

PARTICIPANT STATEMENT:

The test has been explained to me and I consent to participate. I have had the opportunity to ask questions.

____
Signature of Participant Date

I wish to receive project results:

____
Signature of Participant Date

INVESTIGATORS STATEMENT:

I have offered an opportunity for further explanation of this test.

______________________ ______________
Signature of Researcher Date

______________________ ______________
Signature of Researcher Date

______________________ ______________
Signature of Researcher Date

For additional questions concerning Human Subject Research Review Committee policies and procedures, please contact Professor Huizinga at (616) 895-2472.

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(616) 530-3085 (H)

APPENDIX G

ANTHROPOMETRIC PARAMETERS

Parameter	Description
Total Body Mass	Measure (on a scale accurate to 0.01 kg) the mass of subject with all clothes except underwear removed
Height	With the subject standing, measure the distance from the floor to the top of the apex of the head
ASIS breadth	With a beam caliper, measure the horizontal distance between the anterior superior iliac spines
PELVIS:	
Pelvic height	With a sliding caliper, measure the distance from the pubic tubercles to a point bisecting a line drawn which connects bilateral ASIS's
Pelvic depth	With a sliding caliper and the subject in a sidelying position, measure the distance from ASIS to PSIS
THIGH:	
Thigh length	With a sliding caliper, measure the vertical distance between the superior point of the grater trochanter of the femur and the superior margin of the lateral tibia
Midthigh circumference	With a tape perpendicular to the long axis of the leg and at a level midway between the trochanteric and tibial landmarks, measure the circumference of the thigh
CALF:	
Calf length	With a sliding caliper, measure the vertical distance between the superior margin of the lateral tibial and the lateral malleolus
Calf circumference	With a tape perpendicular to the long axis of the lower leg, measure the maximum circumference of the calf
KNEE:	
Knee diameter	With a spreading caliper, measure the maximum breadth of the knee across the femoral epicondyles

FOOT:

Foot length	With a beam caliper, measure the distance from the posterior margin of the heel to the tip of the longest toe
Malleolus height	With the subject standing, use a sliding caliper to measure the vertical distance from the standing surface to the midpoint of the lateral malleolus
Malleolus width	With a sliding caliper, measure the maximum distance between the medial and lateral malleoli
Foot breadth	With a beam caliper, measure the breadth across the distal ends of metatarsals I and V

APPENDIX H

CENTER FOR HUMAN KINETIC STUDIES
ANTHROPOMETRIC MEASUREMENT WORKSHEET

Subject Initials: ____________ Date: ____________________
Gender: M ____ F ____ Age: ______

ANTHROPOMETRIC MEASUREMENT	VALUE	UNITS
Total body mass	_______	kg
Height	_______	in
ASIS breadth	_______	cm
PELVIS:		
Pelvic height	_______	cm
Pelvic depth	_______	cm
THIGH:		
R. Thigh length	_______	cm
L. Thigh length	_______	cm
R. Midthigh circumference	_______	cm
L. Midthigh circumference	_______	cm
CALF:		
R. Calf length	_______	cm
L. Calf length	_______	cm
R. Calf circumference	_______	cm
L. Calf circumference	_______	cm
KNEE:		
R. Knee diameter	_______	cm
L. Knee diameter	_______	cm
FOOT:		
R. Foot length	_______	cm
L. Foot length	_______	cm
R. Malleolus height	_______	cm
L. Malleolus height	_______	cm
R. Malleolus width	_______	cm
L. Malleolus width	_______	cm
R. Foot breadth	_______	cm
L. Foot breadth	_______	cm

Comments: ____
____
____
____

Examiner: ____