Data on Gait Characteristics of Four, Five, and Six Year Old Children Using Three Dimensional Video Motion Analysis

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DATA ON GAIT CHARACTERISTICS OF FOUR, FIVE AND SIX YEAR OLD CHILDREN USING THREE DIMENSIONAL VIDEO MOTION ANALYSIS

by

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B.S. June 1986, Oakland University of Michigan

A Thesis submitted to the Faculty of

Old Dominion University in Partial Fulfillment of the

Requirement for the Degree of

Advanced Master of Science

Old Dominion University

November, 1995

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ABSTRACT

The purpose of this study resulted from a need to gather and analyze data on gait characteristics of normal children using the Peak Performance Technologies, Incorporated system, initiate a data base for the Motion Analysis Center at Old Dominion University and compare a computerized motion analysis system to studies using different methods. Fifteen children, aged four to six, were evaluated during gait using a video-based computerized motion analysis system manufactured by Peak Performance Technologies, Incorporated. The gait characteristics studied were stride length, cadence, angular displacements and angular velocities of the pelvis, hips, knees and ankles. The results showed that methods to measure angular displacements of the pelvis as well as femoral and tibial rotation were unreliable. Hip displacements in the sagittal plane showed increased flexion of fifteen degrees when compared to previous studies but were in agreement with hip motions in the frontal plane. Angular displacements of the knee and ankle were in agreement with previous studies except at terminal stance, increased knee flexion was measured. Cadence was in agreement with previous studies however this study had a large standard error and is not considered to be a desirable method for data collection. No studies were found with which to compare angular velocities of the pelvis and lower extremities. This information will serve as a baseline for future studies.

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Chapter 1.

INTRODUCTION

The purposes of this research were to gather and analyze data on the spatial and temporal gait characteristics of fifteen normal children, specifically step length, stride length, cadence, angular displacement and angular velocity of the pelvis, hips, knees and ankles, using a video-based computerized motion analysis system manufactured by Peak Performance Technologies, Incorporated.*

Traditionally physical therapists have used observation to describe gait and the pathomechanics of gait, but limitations exist in the use of purely observational evaluations.[1,2,3] Todd stated that observational analyses do not generate objective measurements, are not easily interpreted and do not accommodate changes over time.[4] The use of video-based computerized motion analysis systems and gait laboratories provide a more scientific evaluation of the gait cycle which allows for decreased subjectivity in clinical decision making.[5] Rose studied the gait of children with neurologic disorders using numerous methods of gait[1] analysis including observation and computerized three dimensional kinetic and kinematic analysis.[6] She concluded that due to the

* Peak Performance Technologies Incorporated, 7388 S Revere Pkwy, Ste 801, Englewood, CO 80112

complexity of the primary deviations, compensa2 tory patterns and the multiplanar involvement of the children's gait, observational gait analysis of these children is inadequate.[6] Rose also added that three dimensional computerized motion systems aid the physical therapist in making more scientific decisions regarding surgical treatments and their outcomes.[6]

Most research and clinical application of gait analysis has centered around the gait deviations in children with neurologic disorders.[7-16] Sutherland stated that one of the most significant applications of motion analysis is the evaluation of the pathologic gait in children with cerebral palsy.[13] Little information, however, has been published to compare normal children's gait with that of pathologic gait in children with cerebral palsy. This research aims to provide a data base on normal children for the Old Dominion University Gait and Motion Analysis Laboratory to provide a source of comparison with children who demonstrate pathologic gait.

Studies which have collected normative data on children using the Peak Performance Technologies, Inc., System have not been reported in the literature. A need exists to collect normative data using the Peak Performance Technologies, Inc., system and to compare these findings with the findings from other gait analysis systems.

Normative data is also needed on normal children at specific age intervals. Sutherland found significant differences in the normal gait patterns of one, two, three and seven year old children. He reported that children by the age of three displayed adult patterns only with respect to joint rotation. The mature gait pattern was not developed until age seven.[17] DeLuca stated that a child's stable and measurable gait pattern usually developed by about the age of seven.[12] Patrick stated that by age seven, children with neurologic disorders have reached the developmental pattern of neuromuscular control equal to their normal peers but with decreased efficiency.[11]

Literature Review

Leg Length

Scrutton studied the leg lengths of ninety-seven normal children ranging in age from thirteen to fifty-four months old, using foot print sequences. He found mean leg length increased with age. Mean leg length for each age range was provided.[18] These are found in Figure 1.

Spatial Measurements

Step length is defined as the linear distance of initial contact of the feet between sequential points.[19] Step factor is defined as the step length divided by the limb length. This derived measurement allows the determination of whether a longer stride is due to a longer leg length alone.[20] In Scrutton's study of ninety-seven normal children, he concluded that the step factor should increase with age between one and four years of age.[18] Rose-Jacobs, using ink footprints, studied thirty-one children, ages three and five years old, at slow, free and fast speeds.[20] She reported that regarding the three and five year old children, both groups showed longer step lengths at the slower speeds. At the slow and free speeds, the three year old group had increased variance of step length.[20]

Sutherland evaluated one hundred and eighty-six children, ranging in age from one to seven years of age.[17] He concluded that step length increased with age but the most rapid change was from age of onset of walking to two and one-half years old.[17] Normative data on children ages one to five years old are summarized in Table 1.

Stride length was also evaluated in Rose-Jacobs study.[20] She found that stride length was greater in the five year old group at the free and fast speeds but not significantly different at the slow speeds. Variance of stride length was higher in the three year old group at the free and slow speeds.[20] Beck evaluated the stride length of fifty-one normal children, age ranges from eleven months to fourteen years, using photocells in the floor.[21] He reported that the parameters of time and distance were dependent on age.[21] Todd studied eighty-four children whose ages ranged from thirteen months to twelve years.[4] He concluded that stride length increased as walking speed and height increased.[4] When stride length was correlated with the subject's height, stride length showed no changes with age and remained relatively constant.[4] For a tabulated summary of stride length for children ages eleven months to fourteen years, see Table 2.

Sutherland and Burnett reported angular displacements of the pelvis during gait.[17,22] Both of these authors have reported significant changes in anterior pelvic tilt in the development of normal gait in very young children.[17, 22]

Sutherland studied one hundred eighty-six normal children between the ages of one and seven years. He found that the one year old children have an increased anterior pelvic tilt as compared to the two year old children and pelvic tilt remained relatively unchanged from two to seven years old.[17] Burnett sequentially filmed twenty-eight children in two dimensions to document developmental changes in relation to gait.[22] The children ranged in age from nine months to eleven years old. She also concluded that anterior pelvic tilt was delineated between one and two years.[22]

Several researchers have examined pelvic rotation in children. Sutherland reported that no significant differences were found in pelvic rotation between the one, two and seven year old children and that his results were in agreement with that of adult gait.[17] Burnett reported that pelvic rotation was seen consistently just after the age of one but the onset of pelvic rotation ranged from ten to sixteen months.[22]

Isolated studies of pelvic obliquity were noted. In Sutherland's research, two and seven year old children demonstrated similar characteristics throughout the gait cycle.[17] Significant changes were shown from one to two years old. Sutherland reported that during single limb stance, one and two year old children showed a depression of the pelvis ipsilaterally while the seven year old children maintained the pelvis in neutral, similar to that of adults. During swing, the one year old children displayed pelvic elevation ipsilaterally while the two year old children were approaching a more neutral position. Conversely, the seven year old children showed slight depression of the pelvis. Adults studied showed a more neutral pelvic position.[17]

Various authors have assessed the kinematics of hip motion in children.[17,23-25] Bruin studied fifteen children with cerebral palsy and six normal children using a microcomputer-based locomotion analysis system involving foot switches.[23] In his results, there was increased hip range of motion in the sagittal plane as the speed of walking increased. The hip showed a twenty degree increase in range of motion with an increase of 1.2 meters per second.[23] Sutherland reported that the forty degree angle of hip flexion occurring at foot strike did not change between ages two and seven years old.[17]

Sutherland also found that the gait of two year old children differs from that of one-year old children in that external rotation of the hip is decreased.[17] In comparing three year old children with the two year old children, he reported that the base of support was decreased. The three year old children displayed rotation at the hip similar to that of adults in that at foot strike there was five degrees of external rotation, internal rotation during stance phase and about seven degrees of external rotation during swing.[17]

Staheli and Svenningsen used goniometric measurements to assess hip rotation.[24,25] Both researchers found changes in hip rotation with age. Staheli found internal rotation to be greatest in childhood, ranging from forty to sixty degrees in females and fifty to sixty-five degrees in males. Internal rotation was considered abnormal if it was greater than seventy degrees.[24] Svenningsen reported that females had a decrease in internal rotation from four to eleven years old with a significant increase in internal rotation from age fifteen to adulthood.[25] Males, eight and older, showed a general decrease in internal rotation to adulthood, totaling thirteen degrees.

External rotation also decreased with age until adulthood and was greatest during infancy.[24] Staheli reported there were no gender differences found. The average range of external rotation was twenty-five to forty-five degrees.[24] Svenningsen reported males had increased external rotation from four to six years of age as compared to females, averaging forty-eight and forty-four degrees respectively.[25] Svenningsen also found that of the seven hundred sixty-one normal subjects studied, sixteen percent were observed to have in-toeing gait. Thirty percent of these subjects were four years old and four percent of the subjects were adults. A significant increase in internal rotation and a decrease in external rotation, measured goniometrically in supine, was noted in the subjects with in-toeing gait.[25]

Sutherland reported hip motions in the frontal plane.[17] He found that similar patterns were present between the one, two, three and seven year old children and adults. During right initial contact the hip increased in adduction followed by abduction to neutral during left toe off. Upon left initial contact, the right leg demonstrated increased abduction and during left toe off, the right leg approached a more neutral position.[17] The main differences between the age groups were in amplitude. All of the children studied showed some degree of abduction beyond neutral, ranging from five to ten degrees while the adults studied showed abduction to neutral only. The adults studied displayed adduction to ten degrees at initial double stance. The maximal values for adduction in the one and two year old children were zero and five degrees respectively. The seven year old children displayed eight degrees of adduction at the end of initial double stance, similar to that of adults.[17]

On analysis of sagittal plane knee kinematics, various authors agreed that increased knee flexion and extension occurred during stance in two year old children than seven year old children.[17,22] Sutherland characterized two year old children to have greater knee flexion occurred after right initial contact and that knee extension occurred before toe-off. He also noted only a three degree difference was measured at the knee between the seven and two year old children.[17] Burnett reported that knee flexion at midstance was present just after two years. The mature knee mechanism, termed the double knee-lock pattern by Burnett, required extension, followed by flexion and then extension throughout stance, was present by age three.[22]

Torsional problems in the lower extremity were studied by Fabry on one-hundred twenty-three children, ages five to eleven years old who exhibited in-toeing gait. Thirty percent had internal tibial torsion as evidenced by computerized tomography.[26] Normal values of seven year old children for tibial torsion were thirty degrees.[26] Fabry reported that increased tibial torsion did not correlate positively with internal hip rotation.[26]

Studies of ankle kinematics in the sagittal plane have also been reported in the literature. Sutherland found that the one year old child has a flat foot strike at initial contact. One year old children present with a mild foot drop which was not present at age two.[17] At age two, initial contact is made by heel strike instead of foot flat.[17] Burnett reported that consistent heel strike occurred just prior to age three.[22] In Sutherland's work, the pattern of the one, two and seven year old children's ankle kinematics was similar to that of the adults but, like the hip, amplitude was different. The adult total excursion of sagittal plane motions of the ankle was thirty five degrees, ranging from twenty-five degrees of dorsiflexion at toe off to ten degrees of dorsiflexion at the end of initial double stance. The ranges of the one, two and seven year old children were twenty-five, twenty-five and thirty degrees, respectively. Maximal plantarflexion was achieved at approximately toe off while maximal dorsiflexion was reached at the end of initial double stance.[17]

Temporal Measurements

Various authors have determined cadence in children.[4,20,21,23] Rose-Jacobs measured the cadence in three and five year old children and found the two groups were not significantly different. Cadence was significantly higher in the five year old group at the fast speed only.[20] Beck reported that cadence decreased with age from one-hundred eighty-four steps per minute in the one and two year old children to one hundred ten steps per minute for the sixteen and seventeen year old children. He concluded the gait patterns of normal children are age-dependent and velocity dependent.[21] A comparison is found in Figure 2.

Although gait in normal children has been studied by many researchers, kinematic and kinetic data using the Peak Performance Technology Kinematic System have not been published. Since data collection methods and data reduction methods could affect the variability of measurements, it is important for the Gait and Motion Analysis Laboratory at the School of Community Health Professions and Physical Therapy at Old Dominion University to maintain a data bank of using its gait analysis system.

Purposes of Research

The purposes of this research are three-fold. The first objective is to collect and analyze data on kinematic gait characteristics of normal children using the Peak Performance Technologies, Inc., system. This includes documentation of relative joint displacements of the pelvis, hips, knees and ankles, relative angular velocities of the pelvis, hips, knees and ankles, and measurement of stride length, leg length and cadence.

The second objective of this research is to establish gait measurements on children ages forty-five to seventy-two months in the Gait and Motion Analysis Laboratory at the School of Community Health Professions and Physical Therapy at Old Dominion University. These measurements will serve as part of a data base from which to compare gait analysis values in normal children with those of other normal children and with children who demonstrate pathologic gait.

The third goal of this research is to compare the results of this research using a video-based computing motion analysis system with previous studies using different recording methods.

Chapter 2.

METHODS

Subjects

Fifteen children, ages four to six years old, were analyzed in the Gait and Motion Analysis Laboratory at the School of Community Health Professions and Physical Therapy at Old Dominion University in Norfolk, VA. Eligibility criteria for the subjects were that each child would have no significant neurologic, orthopaedic or metabolic disease and be able to ambulate independently without an assistive device and without pain. The children were selected from the kindergarten class of the campus child study center. Parents signed a consent form at the Child Study Center. The University Human Subjects Committee reviewed and approved the study. The child's teacher was instructed in the procedures of this study. Teachers provided information about the children's birth dates.

Operational Definitions[19]

Angular velocity:	a change in the angular position of a segment with respect to time
Joint displacement:	a change in joint position
Heel strike:	the gait event where the heel makes contact with the

	ground, normally the initiation of stance phase
Initial contact:	the gait event where any part of the foot first makes contact with the ground; in normal gait, initial contact is made with heel strike
Toe off:	the gait event where the toe leaves the ground
Stance Phase of Gait:	the period of foot contact with the ground, beginning with initial contact and ending with toe off
Step Factor:	step length divided by the lower limb length
Swing Phase of Gait:	the phase of no foot contact with the ground, beginning with toe off and ending with initial contact

For other definitions and measurement techniques, please refer to Appendices One through three.

Procedures

A brief screening to rule out participants with orthopedic or neurologic abnormalities was performed. The screening included observation of postural alignment in standing and gross observation of the gait cycle prior to filming.

The subjects were dressed in black turtleneck shirts, black tights and wore no shoes. The black garments enhanced the optical contrast of reflective markers placed on the subjects.

Passive retro-reflective markers, 28 millimeters in diameter, were attached to the following bony prominences with double-sided tape: spinous process of S2, bilateral ASIS, bilateral greater trochanters, bilateral lateral condyles of the femur, bilateral lateral malleoli and the base of the bilateral fifth metatarsals (see Table 3). To measure rotation of the femurs, ten centimeter wands were attached posteriorly to the midshafts of the thighs. To measure rotation of the tibia in the transverse plane, a ten centimeter wand having markers at its base and tip was attached to the midshaft of the right calf.

A cartoon poster of "Simba" was hung at the end of the walkway. The children were instructed to walk to the other side of the room, turn and walk back to the examiner or to walk over and see "Simba". Three walking trials were videotaped for each child to ensure that at least one view was usable for analysis. Once filming was completed, the subjects were free to leave.

Instrumentation

Of the four cameras utilized, one camera was placed in each corner of the viewing area in the laboratory. Each camera was placed at a forty-five degree angle from the center of the longitudinal axis of the walkway (see Figure 3). Each camera was a Panasonic recording camera with a seventy-five millimeter lens. The cameras were mounted on sturdy tripods at a height of ten feet above the walkway. All cameras were synchronized with genlock for simultaneous, frame by frame recording.

Once the camera setup was measured, the cameras were not moved or in any way altered. A two-hundred watt light source was positioned near each camera to provide illumination of the reflective markers. Super VHS normal speed video tape was used to film the subjects. The shutter speed of cameras 3 and 4 was 0.001 seconds; the shutter speed of the other cameras was 0.002 seconds. According to Sutherland, these are acceptable values for studying human gait.[27]

Calibration of the cameras was performed prior to the data collection by videotaping a calibration frame (two meters by two meters by 1.31 meters) supplied by the manufacturer. Twenty-four white reflective balls are on the frame with a known distance apart and are digitized manually. These points are compared with the known points on the calibration frame.

The computer utilized for data collection used a mathematical process called direct linear translation which transferred the two-dimensional data into three dimensional points. To assess the amount of error in manually digitization of the calibration frame, the average volume percent error was calculated. This value yielded the amount of error in the transformation of data from two to three dimensional data points and was expressed as a percentage. The recommended acceptable average volume percent error for calibration is less than 0.500.[28] The average volume percent errors of the calibration for this study were within acceptable ranges. See Table 4 for numerical values.

The motion analyzing system used in this study consisted of the Peak Performance Technologies, Inc., (PPTI) system, a video cassette recorder (VCR) controlling board, and a video frame-grabber. These were used with a computer, a Panasonic editing VCR, a monitor and a PPTI automatic digitizing software package. The time code was placed on each video tape simultaneously using a time code generator.

Data Collection

At the beginning of the each of the three filming sessions, the calibration frame was positioned in the center of the walkway so that all twenty-four balls on the calibration frame were visible by each camera. The calibration frame filled the entire viewing area from the camera. The calibration frame was filmed for at least sixty seconds. The subjects were instructed to walk on the ten foot by five foot walkway at a self-directed pace while they were being video-taped. The subjects walked to the end of the walkway, turned around and walked back to the researcher. This was done three times. The child was required to perform two strides in the area of the calibration frame for the view to be acceptable. This requirement helped to maintain the calibration and accuracy of the system. [28]

Once the data was captured on video tape for each subject, it was then converted to the computer system for digitization. The researcher chose the best of three trials, ensuring that the maximum number of markers were visible from each camera angle. Each trial was designated by a specific time code and the first two frames were manually digitized. This procedure identified the markers to the software system. The PPTI automatic digitizing software then determined the successive marker locations based on the previous parameters and automatically tracked the position of each marker during the gait cycle for each video. During normal gait, the distal upper extremity may cover or hide the pelvic and greater trochanteric markers from the cameras. The researcher was able to manually digitize the markers in those cases where the markers were hidden and estimate their locations. Manual digitization was required when the markers overlapped or juxtaposed. Once the marker was visible again, the automatic digitizing mode restarted and continued for the duration of the frames. Each child was viewed from four video tapes. The same trial on each of the four tapes was viewed from different spatial orientations. Sixty to one hundred frames per video tape were digitized.

All calculations were performed using the Peak Performance Technologies, Incorporated computer software once the data was digitized. The data was then displayed in the form of a trajectory on each child. If an erroneous point or points occurred, the researcher had the option to manually re-digitize a point or set of points on the trajectory. The data was then smoothed using a Butterworth filter with a low frequency cut off of six hertz. This is the recommended level for working with human gait.[8]

Data Analysis

After all the data were collected, graphic displays of angular displacements and angular velocities were printed. Angular displacements and velocities were mathematically averaged using Grey Matter International Incorporated* computer software package and the mean and the standard deviations were calculated. The mean and standard deviation of the demographic data, s[3] pecifically leg length, height and weight, were calculated. Refer to Table 5 for information. Cadence was measured by counting the number of steps in the field of view on the VCR. The time was measured on the VCR counter[4] to the nearest second. Two views were assessed and averaged.

* Grey Matter International Incorporated, 173 Otis St., Cambridge, MA 02141

Chapter 3.

RESULTS

Fifteen children were evaluated. The results of spatial and temporal measurements will be discussed. Demographic information is displayed in Table 5. Because there was little difference among subjects in height and leg length, the children were analyzed as one group.

Spatial Measurements

The average stride length was calculated to be 806 millimeters +/- 360 mm. See Tables 6 and 7 for a list of the horizontal velocities used. Step length was not recoreded due to errors in data collection. The software package did not allow for a measurement of step length so these results are not included.

Cycle divisions commence as the right leg begins heel strike at the beginning of initial double stance, followed by single right limb stance and left swing, terminal double stance of the right limb and swing of the right limb.[19] Some of the data regarding the angular displacements were not usable because of technical difficulties that contaminated the values. Thus, children #4, 9, 11, 12, and 13 were not utilized for this portion of the research. Please refer to Table 8 for a summary of angular displacements as they relate to cycle divisions.

After the fourth and eighth child were filmed, the calibration frame was rotated an slightly. Because the amount of rotation was not recorded, procedural errors in data collection resulted. Because the pelvis motions were measured in relation to the transverse plane, the amount of deviation from the axis of rotation was reqired but not recorded. Therefore,measurements of pelvic rotation, pelvic tilt and pelvic obliquity could not be averaged because of the procedural error in data collection. The results will indicate the direction and amplitude of displacement but will not state position in space.

Pelvic Motion

See Tables 9 a through e for graphs of pelvic motions. The pelvis was externally rotated at initial contact of the right leg, had increased external rotation of the right pelvis at right terminal stance of approximately five degrees and during swing of the right limb had a decrease of approximately five degrees. The standard deviation, +/- thirty degrees, was relatively large for this measurement. Graphs of the right and left pelvic obliquity appeared identical and ranged from one to four degrees of motion throughout the gait cycle. The standard deviation was calculated to be +/- two degrees. The pelvis maintained anterior pelvic tilt throughout the gait cycle, increasing during initial double limb stance and decreasing during swing phase. The range of anterior tilt was three degrees with a standard deviation of +/- two degrees.

Hip Motion

See Table 10 a through d for averaged graphs of hip motions and standard deviations. The hip, at initial contact of the right limb, was in approximately ten degrees of hip flexion and approximately five degrees of adduction. Abduction to neutral and gradual right hip extension occurred during single limb stance and terminal double stance. During swing of the right leg, the hip adducted approximately less than five degrees and achieved its maximal amount of flexion of ten to twenty degrees. The standard deviation of flexion and adduction is +/-

fifteen degrees and +/- five degrees respectively.

Knee Motion

See Table 11a and b for averaged graphs of knee motion and standard deviations. The right knee at initial contact was in approximately ten degrees of flexion and continued to flex to approximately twenty-five degrees of knee flexion during double limb stance. Upon toe off of the contralateral limb and beginning with single limb stance, the right knee extended to approximately twelve degrees of zero and remained extended throughout stance. Nearing the end of single limb stance, right knee flexion occurred and continued during terminal double limb stance. At terminal swing of the right limb in preparation for heel strike, extension occurred. The standard deviation was +/- five degrees.

Ankle Motion

See Table 12 a and b for averaged graphs of ankle motion including standard deviations. The right ankle was in approximately ten degrees of plantarflexion at initial contact with a gradual pattern of dorsiflexion carried through single limb stance. Nearing the end of right single limb stance, plantarflexion of approximately ten degrees occurred. The right ankle continued plantarflexion throughout terminal double stance and reached maximal plantarflexion of twenty degrees at toe off, beginning swing phase. During swing phase gradual dorsiflexion to neutral occurred. The standard deviation was approximately +/- ten degrees.

Temporal Measurements

The average cadence was 163 steps per minute with a standard deviation of 34.2 steps per minute. Refer to Table 13 for a summary of data.

Angular velocities of the hips, knees and ankles will be described as they relate to cycle divisions. Data regarding pelvic velocities will not be used due to procedural errors in data collection. Please refer to Table 14 for a summary.

Hip Velocities

Please refer to Tables 15 a through d for graphs of averaged hip velocities. During initial double stance, there was a significant increase in velocity of the right leg into hip extension, reaching its maximum of approximately one hundred degrees per second just after single limb stance. During single limb stance, there was a decreased velocity of hip extension, approaching zero. Upon terminal double stance of the right leg, increased hip extension velocity occurred. After toe off of the right leg during swing, the right hip reached its maximum velocity of extension of 100 degrees per second and
progressed toward neutral in preparation of right initial contact.

A change of velocity of 75 degrees per second from adduction to abduction occurred from right initial contact to right toe off. During single limb stance the velocity of right hip adduction was approximately 50 degrees per second. At terminal double stance, the maximum velocity of abduction of the right hip was achieved and then approached neutral as right toe off occurred. During swing, increased velocity into adduction of the right hip occurred.

Knee Velocities

Please refer to Table 16 a and b for the graphs of averaged knee velocities. At initial contact the knee velocity was near zero and began to increase in flexion, reaching its maximum of 220 degrees per second prior to right single limb stance. During right single limb stance, the velocity of extension increased to 100 degrees per second. Nearing terminal double limb stance of the right lower extremity, the velocity of the knee neared neutral. At right terminal double limb stance and throughout this stage, the right knee flexion velocity was maintained at approximately 200 degrees per second. As swing occurred there was a moderate increase in extension velocity, reaching its maximum of slightly over 200 degrees per second.

Ankle Velocities

Please refer to Table 17 a and b for the graphs of averaged ankle velocities. The velocity of the right ankle at initial contact was a progression into plantarflexion, peaking just prior to single limb stance. During right single limb stance, there was an increased velocity into dorsiflexion, reaching its maximum at terminal double limb stance. During swing, there was a increased velocity of plantarflexion.

Chapter 4.

DISCUSSION AND CONCLUSIONS

The present study resulted from a need to gather and analyze data on gait characteristics of normal children using the Peak Performance Technologies, Incorporated system, initiate a data base for the Motion Analysis Center and compare a computerized motion analysis system to studies using different methods.

Measurements of the motions of the pelvis were highly variable. In addition, there were technical difficulties and procedural errors that made the pelvic measurements invalid. The reliability defined as the repeatability of these measurements or consistency is questionable.[30] Due to the size of the children and the marker placement, the technique utilized in this research may not be optimal. Gage and Sutherland used a metal rod perpendicular to the sacrum as well as markers on the anterior superior iliac spines for measurement of pelvic motions rather than the marker placements used in this study.[16,17]

An assessment of parallel-form reliability, meaning the agreement of alternative methods of measurement to this method, would also be beneficial when assessing femoral and tibial rotation with the use of the wands. The wand measurements were highly variable and not usable for this study. The wands were positioned posteriorly which created much difficulty in digitization due to moderate overlapping primarily when maximal knee flexion occurred. There were also difficulties with the lateral condylar markers blending with the femoral wand and tibial wand markers. Gage used metal rods which may be more sturdy than the wooden rods utilized in this research.[16] The metal rods may significantly reduce the amount of instability of the markers evident with this system and minimize the recording of movement errors. Gage positioned the wands more laterally on the subjects which reduced the blending affect with adjacent markers.[16] Sutherland measured femoral rotation using geometric methods, requiring only a tibial wand.[17] Using these reported methods would greatly reduce the number of markers and wands required, thus minimizing error associated with digitization and leading to improvement in content validity.

Another issue associated with the content validity of the research related to experimental effects. The children were not in a natural setting and although attempts were made to distract them from concentrating on ambulation, experimental effects are assumed. For example, a few children appeared to be frolicking and playing either by walking very stiffly or very precisely.

When compared with previous studies, the results of this research will be discussed in terms of demographic, spatial and temporal measurements.

Demographic Measurements

The average age of the children in this study was 5.5 years. In Slaton's study, the average age of children was 3.4 years old.[29] This age discrepancy may account for the significantly greater values found in this study regarding leg length, height and weight measurements.

Spatial Measurements

Stride length was in agreement with the results of Rose-Jacob's study regarding five year old children at the free speed.[20] Stride length was less than that of the seven year old children studied by Sutherland as expected.[17] The results stride length in this study were significantly less than the values stated by Rose.[6] This may partly be due to different populations studied. This study limited subjects to four through six year old children and Rose evaluated subjects aged five years old through adulthood.[6]

Motions of the pelvis were highly variable. Sutherland reported at right initial contact that there was pelvic elevation of approximately five degrees in the coronal plane.[17] Because of technical and procedural errors, the amplitude of motion of the pelvis was not measurable however patterns were evident. The results of this study reported eight children (80%) had varying degrees of pelvic elevation. At single limb stance of the right leg, seven children (70%) displayed pelvic depression. Sutherland reported that the pelvis slowly approached neutral from depression after left toe off. During terminal double stance, Sutherland reported a sharp depression of the pelvis however only two children (20%) showed this pattern and only one child (10%) showed the pattern of elevation to neutral during swing as demonstrated by Sutherland.[17]

With regard to pelvic tilt, only four children (40%) showed the same pattern during initial double stance and swing while only two children (20%) showed the same pattern during single limb stance and terminal double stance as reported by Sutherland.[17]

No patterns (0%) were similar to those published by Sutherland regarding pelvic rotation.[17]

Hip motion in the sagittal plane was less variable then pelvic motion. When compared to data on two year old children published by Sutherland, the results showed slight increased flexion during single limb stance and terminal double stance; otherwise the results were in agreement.[17] As compared to the seven year old children analyzed by Sutherland, similar results were found during initial double stance however flexion was slightly higher throughout the remainder of the gait cycle.[17]

Hip motions in the sagittal plane were greater than previous studies. The results of this study also showed increased hip flexion during initial contact and double stance of approximately fifteen degrees when compared to the data published by Rose.[6] Rose however studied five year old children and adults while this study was limited to children aged four through six years old.

Differences in hip motions in the sagittal plane may also be due to lack of gait maturity. Gait maturity is reported by several authors to occur by the seventh year.[1,17,22] Because the children in this study were less than age seven, gait maturity was not expected. Thus, increased hip flexion may be due to the lack of motor development or lack of sufficient developmental skills relating to a more mature gait. The five year old children in this study had increased hip flexion when compared to older children and only slightly increased flexion when compared to the two year old children. Further studies however must be performed with large sample sizes to determine normative values for children between the ages of two and seven years old.

Hip abduction and adduction throughout the gait cycle were in agreement with Rose's work and Sutherland's work with seven year old children.[6,17] This may be due to the small range of total motion of hip abduction and adduction. Total range of motion of abduction and adduction was approximately ten degrees with a combined standard deviation of ten degrees. In the two year old group studied by Sutherland, total range of fifteen degrees of abduction and adduction was reported while a twenty degree range of motion for the seven year old group was noted.[17]

The children aged five and seven were in agreement regarding hip motions in the frontal plane but there was a significant difference between the two and five year old children and between the two and seven year old children. The narrowed base of support increasing with age as documented by Burnett may be a reflection of the decreased range of motion of the hip in the frontal plane, indicative of a more mature gait pattern after age five.[1,20,22]

The motions of the knee during initial contact and right single limb stance were also in agreement with those of Rose and Sutherland however this study reported increased right knee flexion during terminal double stance.[6,17] During swing, the results of this study were in agreement with those of Sutherland's but not those of Rose.[6,17] This may be due to a discrepancy in the ages of the subjects studied. Sutherland evaluated children aged one through seven years old and Rose studied subjects aged five years old through adulthood.[6,17]

The motions of the ankle were in agreement with the results reported by

Rose and the seven year old children reported by Sutherland.[6,17] In comparison to the data of two year old children published by Sutherland, the pattern of motion is similar in that plantarflexion occurred just after initial contact, dorsiflexion was evident during double stance and maximal plantarflexion was achieved during swing phase. The difference however was in the amplitude of motion, being greater in the two year old children than the five year old children.[17] This may be due to the maturation of ankle motion prior to full gait maturity.

Temporal Measurements

In terms of cadence and angular velocities, the results of this study were in agreement with the findings of Rose-Jacobs at the free and fast speeds.[20] These results were also in agreement with the results of Sutherland's study of seven year old children at free speeds.[17] The ranges of cadence for this study as compared to the free and fast speed of Rose-Jacobs study and Sutherland's work were 129-197 steps per minute, 93.53 - 157.73 steps per minute, 131.29 - 179.57 steps per minute and 144 steps per minute, respectively.[17, 20]

No studies were found reporting average velocity of joint motions so no data could be compared with current results, thus the data collected in this research will serve as a baseline with which to compare to adults, children with disabilities and children of other ages.

In conclusion, the purposes of this research were to collect and analyze data on the spatial and temporal gait characteristics of normal children. Gait characteristics of normal children were analyzed using the Peak Performance

Technologies Incorporated system. This collection of data will contribute to a data base for the Motion Analysis Center at Old Dominion University.

Comparisons have been made to other studies. Kinematic measurements of the hip movements in the frontal plane and measurements of the knee and ankle in the sagittal plane were in agreement with other studies reported in the literature. Hip flexion and extension movements displayed the same pattern reported in the literature but the subjects in this study showed increased amplitudes of flexion. Measurements of the pelvis, femoral rotation and tibial rotation in this study were highly variable and are not valid for inclusion in the laboratory's data base.

Recommendations for future gait analysis studies at Old Dominion University include changing the method for geometric calculations for pelvic motions and femoral rotation, using more than fifteen subjects, studying additional age ranges, and conducting reliability studies on the measurement methods.

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Table 1.--Comparison of Step Length and Age of Children Ages One Through Five Years Old

AGE (YEARS)	SCRUTTON[18] CM/CM LEG LENGTH FREE VELOCITY	ROSE-JACOBS[20] CM/CM LEG LENGTH SLOW VELOCITY	FAST VELOCITY	FREE VELOCITY
1	0.73			
2	0.74			
3	0.74	0.71	0.93	0.71
4	0.76			
5		0.64	0.95	0.81

Table 2.--Comparison of Stride Length and Age of Children Ages One Through Fifteen Years		
AGE (YEARS)	**STRIDE LENGTH** (METERS)	
	Beck[21]	Todd[4]
1 - 2	0.72	
6 - 8	0.87	0.70 - 1.00
13 - 15	1.14	

Table 3.--Position of Reflective Markers (Posterior View)

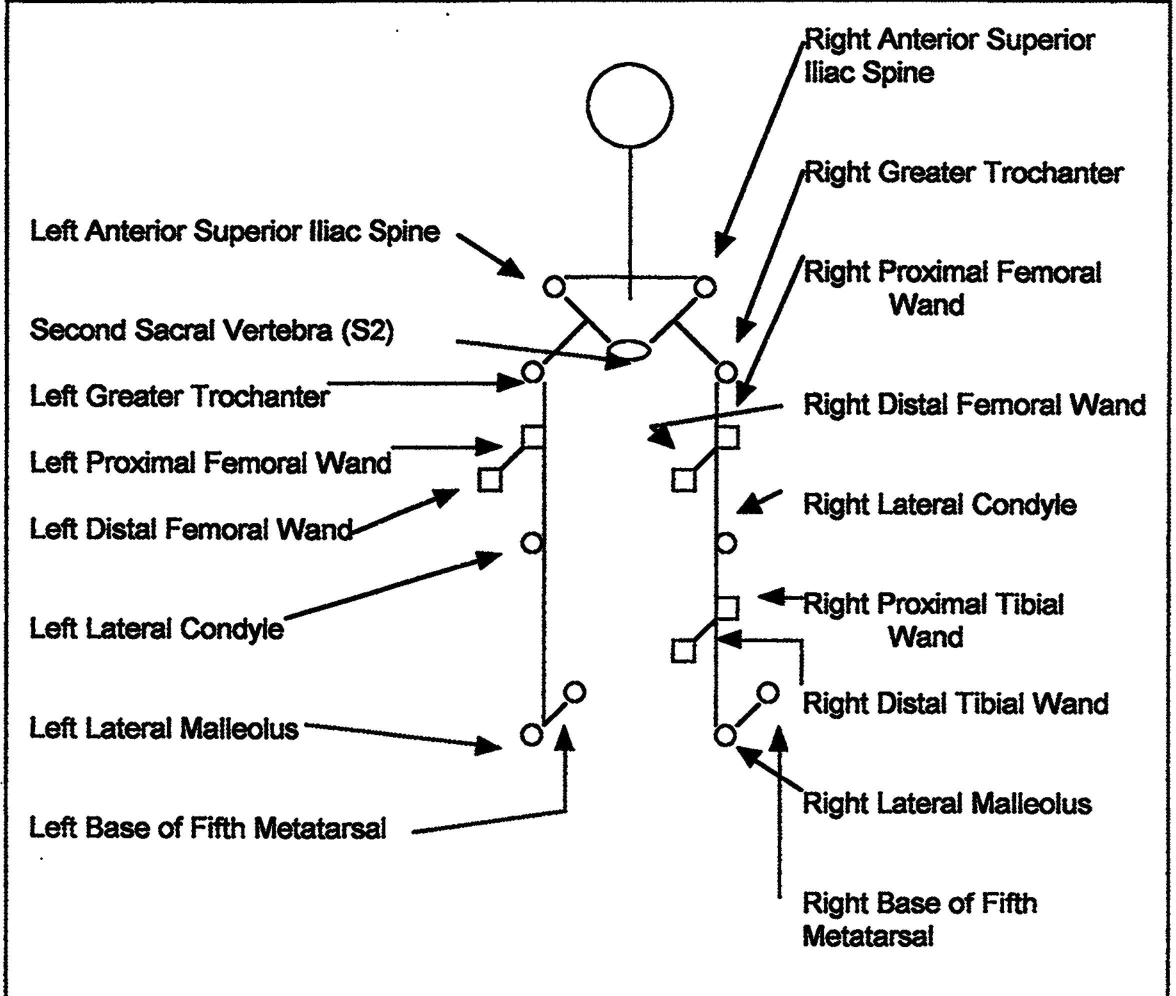


Table 4.--Average Volume Percent Errors, Yielding Amount of Error in Calibration Process	
Children	Average Volume Percent Error
1 - 4	0.236
5 - 9	0.252
10 - 15	0.194
Recommended [27]	< 0.500

Table 5.--Demographic Data on Fifteen Children, Ages Four Through Six Years Old

CHILD	BIRTHDATE	HEIGHT (CM)	WEIGHT (KG)	LEG LENGTH (CM)	
				RIGHT	LEFT
1	1-25-90	110	18	55	56
2	2-06-89	106	17	53	53
3	3-23-89	106	15.5	52	51
4	3-22-89	107	15	52	52
5	4-30-89	107	16	51	51
6	5-12-89	113	22.5	57	57
7	5-24 89	110	18	56	55
8	7-25-90	117	21	58	58
9	7-26-88	115	19.6	57	57
10	8-07-89	109	18	55	55
11	10-22-88	110	17.5	55	55
12	10-26-89	112	21	56	56
13	11-14-89	115	20	60	60
14	11-30-88	113	18.5	56	56
15	11-01-89	107	15.5	51	51
AVERAGE:	**5.5 YEARS**	**111.1 CM**	**18.2 KG**	**54.9 CM**	**54.9 CM**
STANDARD DEVIATION:	**2.5 MONTHS**	**O.82 CM**	**0.48 KG**	**0.56 CM**	**0.58 CM**

Table 6.—Trapezoidal Equation for Measuring Stride Length in Normal Children, Ages Four Through Six Years Old, During Gait

$$S = \frac{\bar{T}_2 - \bar{T}_1}{\quad} (V_y0 + 2V_y1 + \ldots 2V_y(n\text{-}1) + V_yn)$$

$$S = \frac{0.8s - 0s}{2(10)} \left(0 + 2(900) + 2(1250) + 2(1100) + 2(750) + 2(1525) + 2(1100) + 2(800) + 2(1300) + 2(875) + 950 \right)$$

S = 806 mm

S = Length of stride in millimeters

$\bar{T}_1$ = initial time of right heel strike(seconds); $\bar{T}_1$ = 0s

$\bar{T}_2$ = final time of right heel strike (seconds);
T_2 = 47 frames x 1s/60 frames = 0.8 s

V_y = velocity in the Y (horizontal) direction of the fifth metatarsal head

Child	Velocity in Y direction (V_y) mm/s
1	900
2	1250
3	1100
5	750
6	1525
7	1100
8	800
10	1300
14	875

Table 7.--Variables Used to Measure Stride Length in Ten Normal Children Ages Four to Six Years Old, During Gait

Child	Velocity in Y Direction V_y (degrees / s)	Average Velocity - V_y (degrees / s)	(Average Velocity - V_y) ^{2} (degrees^2 / s^2)
1	900	94	8836
2	1250	444	197136
3	1100	294	86436
5	750	56	3136
6	1525	719	516961
7	1100	294	86436
8	800	6	36
10	1300	494	244036
14	875	69	4761

$$s = \sqrt{\frac{(V_y - \overline{V})^2}{n-1}}$$

$\sum$ = 1165374

n = 10

standard deviation = 360 degrees / sec

Table 8.--Summary of Segmental Displacements During the Gait Cycle of Ten Normal Children With Average Age of Five and One-Half Years Old

	INITIAL DOUBLE LIMB STANCE	SINGLE LIMB STANCE	TERMINAL DOUBLE STANCE	SWING
PELVIC TILT	4-5 DEGREES OF ANTERIOR PELVIC TILT	4-5 DEGREES OF ANTERIOR PELVIC TILT	4-5 DEGREES OF ANTERIOR PELVIC TILT	4-5 DEGREES OF ANTERIOR PELVIC TILT
HIP FLEXION & EXTENSION	FLEXION APPROXIMATELY 10 DEGREES	GRADUAL EXTENSION TO ZERO	GRADUAL EXTENSION TO ZERO	MAXIMAL FLEXION OF 20 DEGREES ACHIEVED
HIP ABDUCTION & ADDUCTION	NEUTRAL TO 5 DEGREES OF ADDUCTION	GRADUAL ABDUCTION TO NEUTRAL	MAINTAINS NEUTRAL TO 5 DEGREES ADDUCTION	SLIGHT ABDUCTION OF < 5 DEGREES
KNEE FLEXION & EXTENSION	10 DEGREES OF FLEXION & FLEXES TO 25 DEGREES OF FLEXION	EXTENSION TO LACKING 12 DEGREES OF ZERO FOLLOWED BY GRADUAL FLEXION	CONTINUED FLEXION TO APPROXIMATELY 45 DEGREES	MAXIMUM FLEXION TO 50 DEGREES FOLLOWED BY MODERATE EXTENSION TO APPROX. 20 DEGREES
ANKLE DORSIFLEXION & PLANTARFLEXION	10 DEGREES OF PLANTARFLEXION FOLLOWED BY GRADUAL DORSIFLEXION	DORSIFLEXION TO NEUTRAL AND THEN 10 DEGREES OF PLANTARFLEXION	CONTINUED PLANTARFLEXION OF APPROX. 15 DEGREES	MAXIMAL PLANTARFLEXION OF APPROX. 18 DEGREES FOLLOWED BY GRADUAL DORSIFLEXION

Table 9a. --Graphs of Right Pelvic Rotation of Ten Normal Children Ages Four through Six Years Old During the Gait Cycle

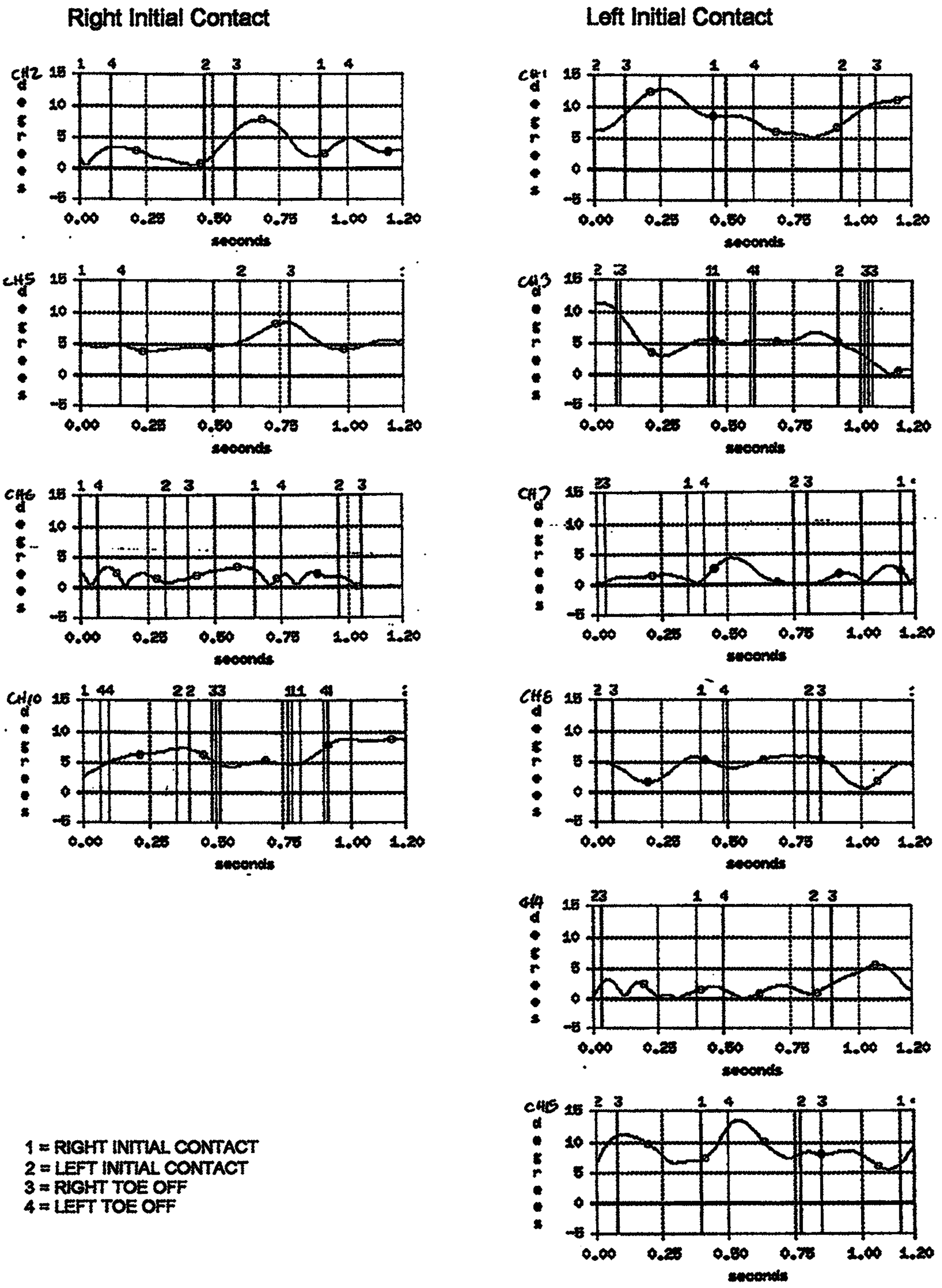


Table 9b. --Graphs of Left Pelvic Rotation of Ten Normal Children Ages Four through Six Years Old During the Gait Cycle

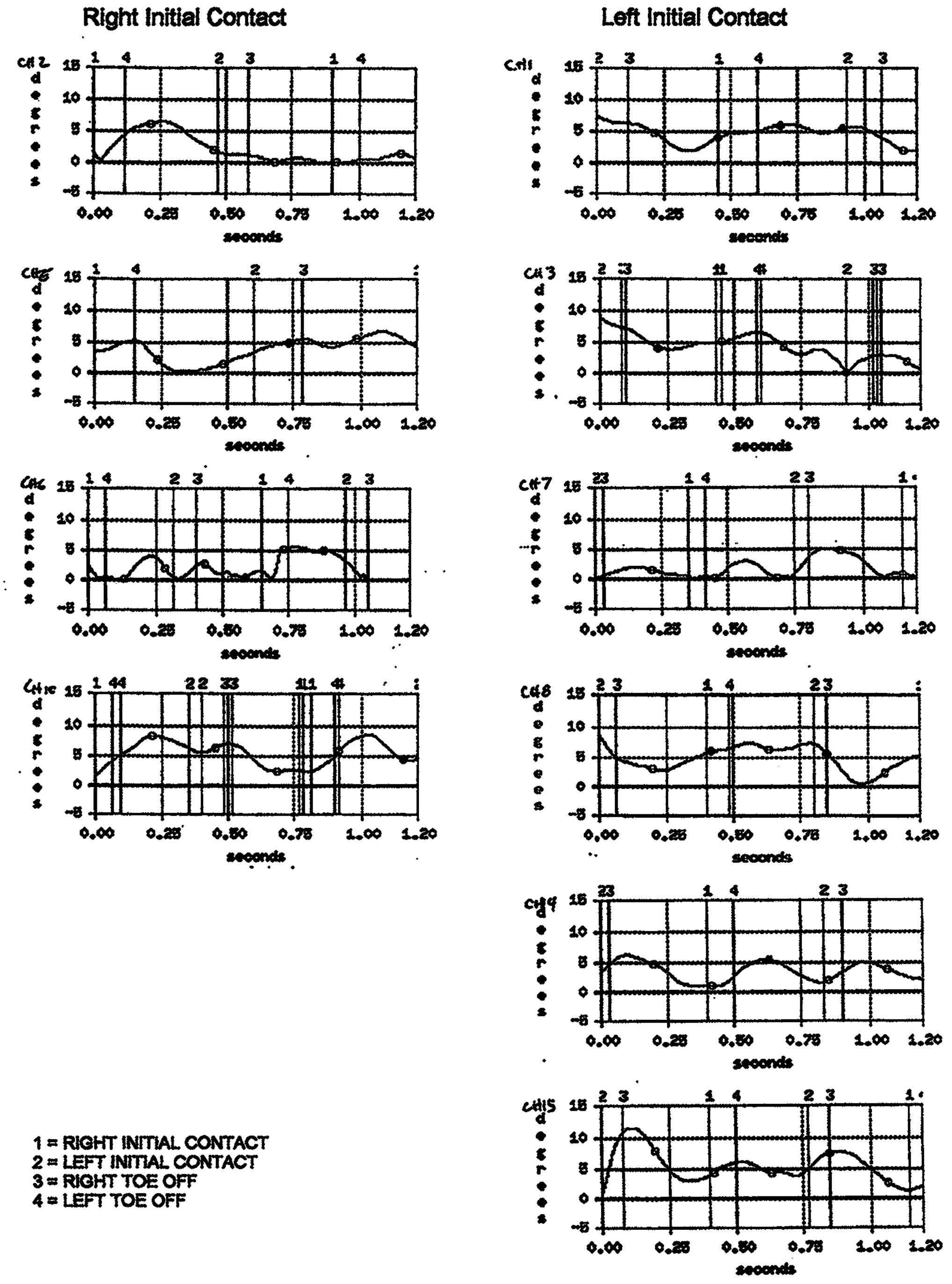


Table 9c. —Graphs of Right Pelvic Obliquity of Ten Normal Children Ages Four through Six Years Old During the Gait Cycle

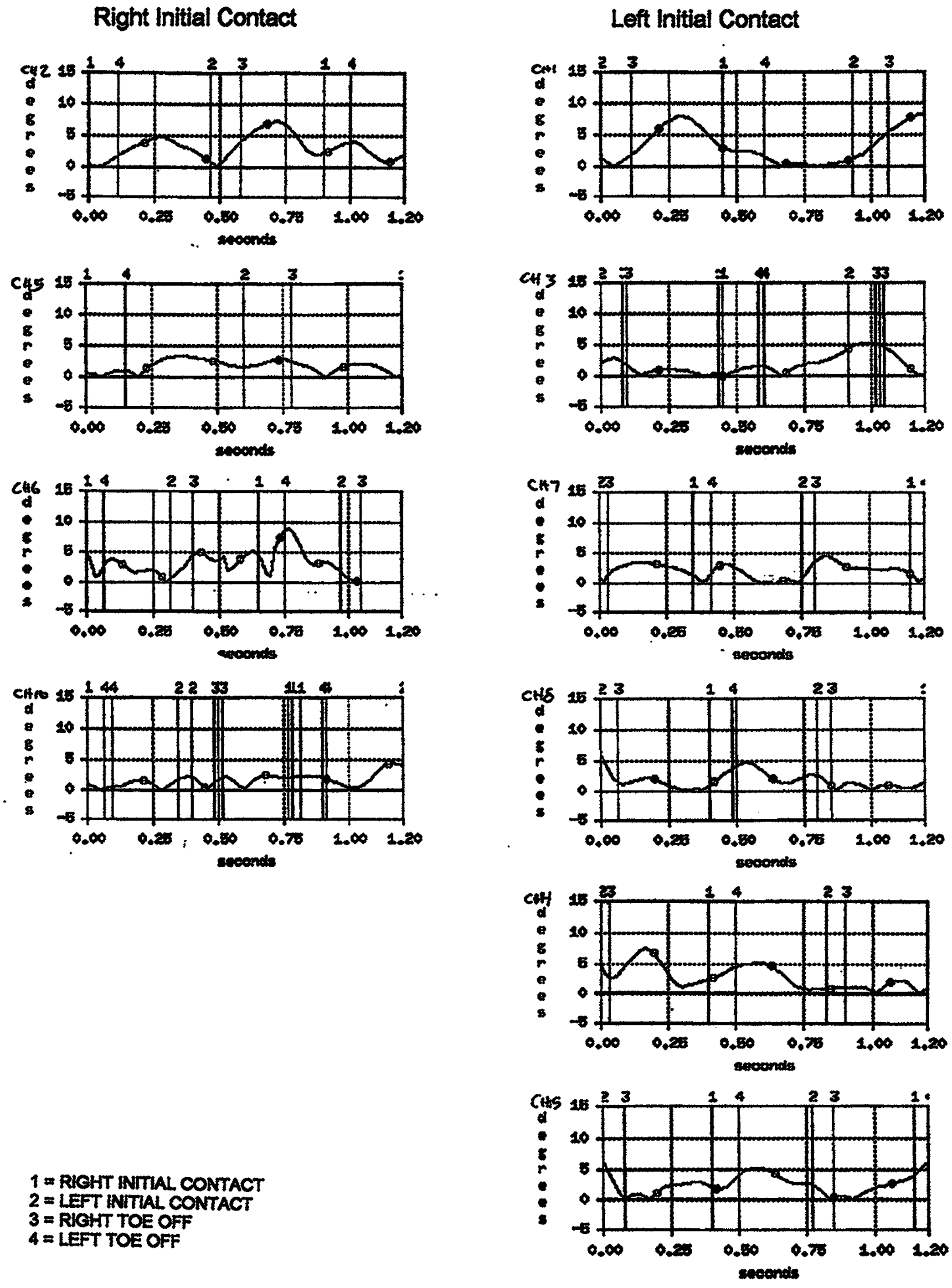


Table 9d. --Graphs of Left Pelvic Obliquity of Ten Normal Children Ages Four through Six Years Old During the Gait Cycle

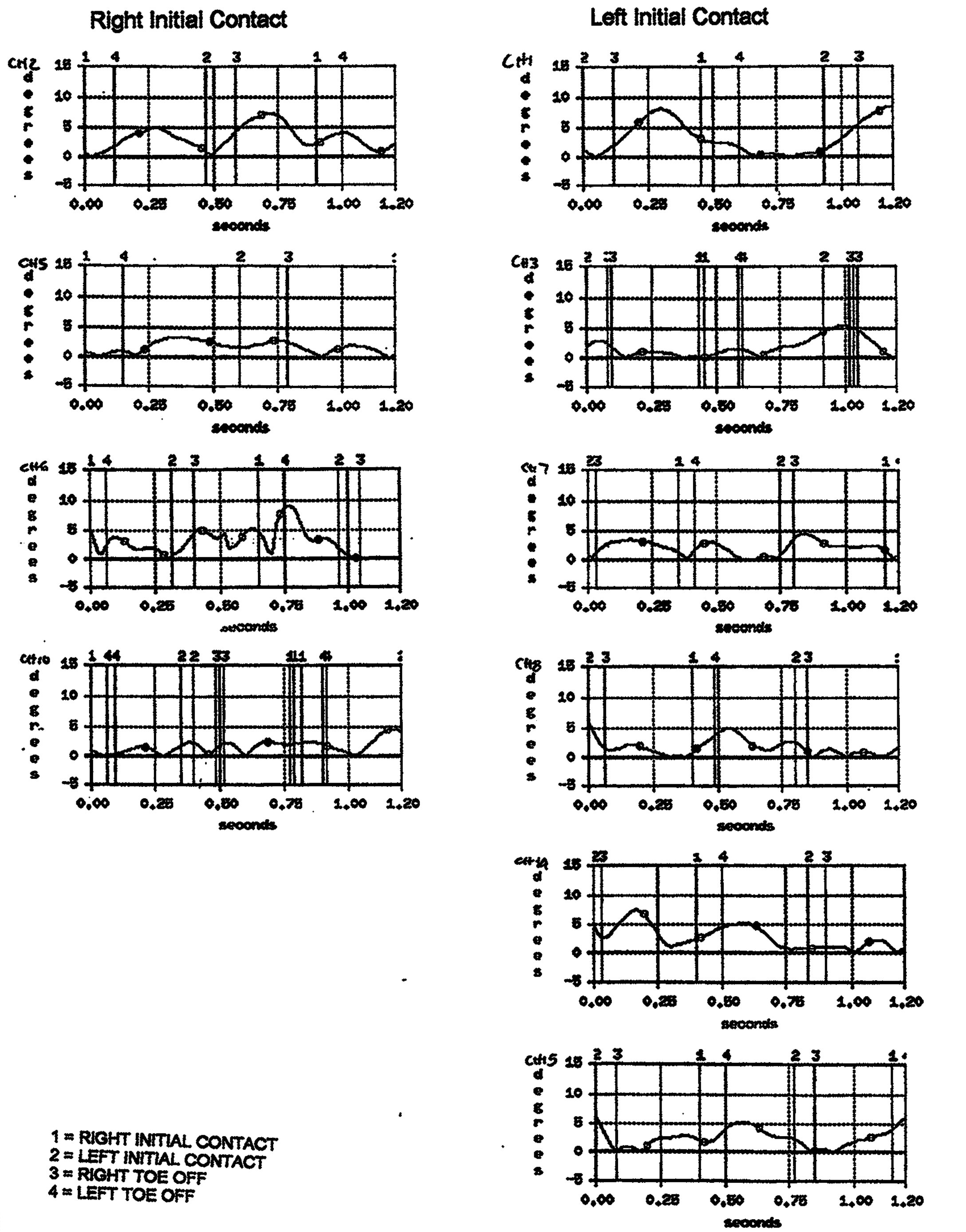


Table 9e. --Graphs of Right Pelvic Rotation of Ten Normal Children Ages Four through Six Years Old During the Gait Cycle

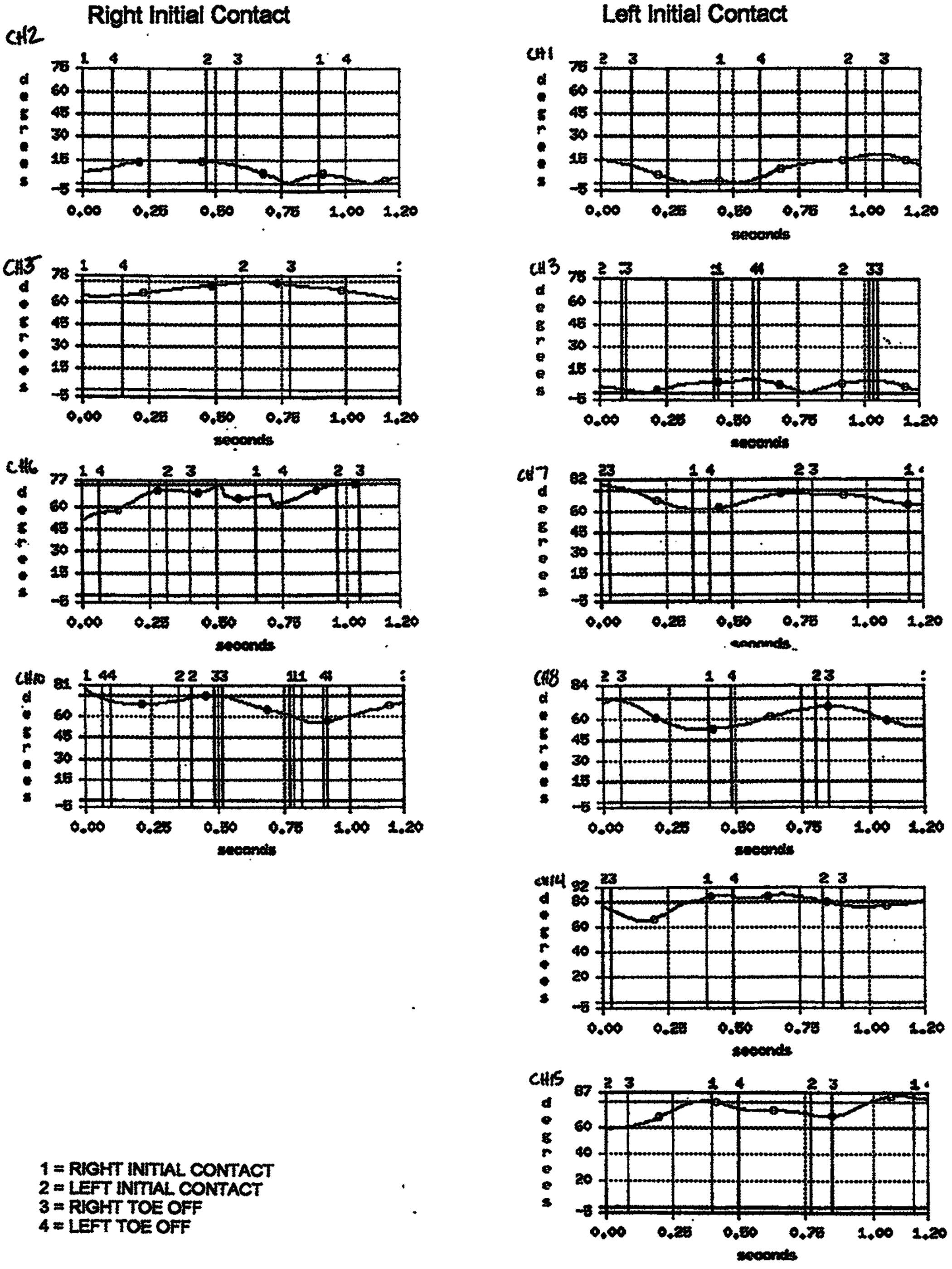
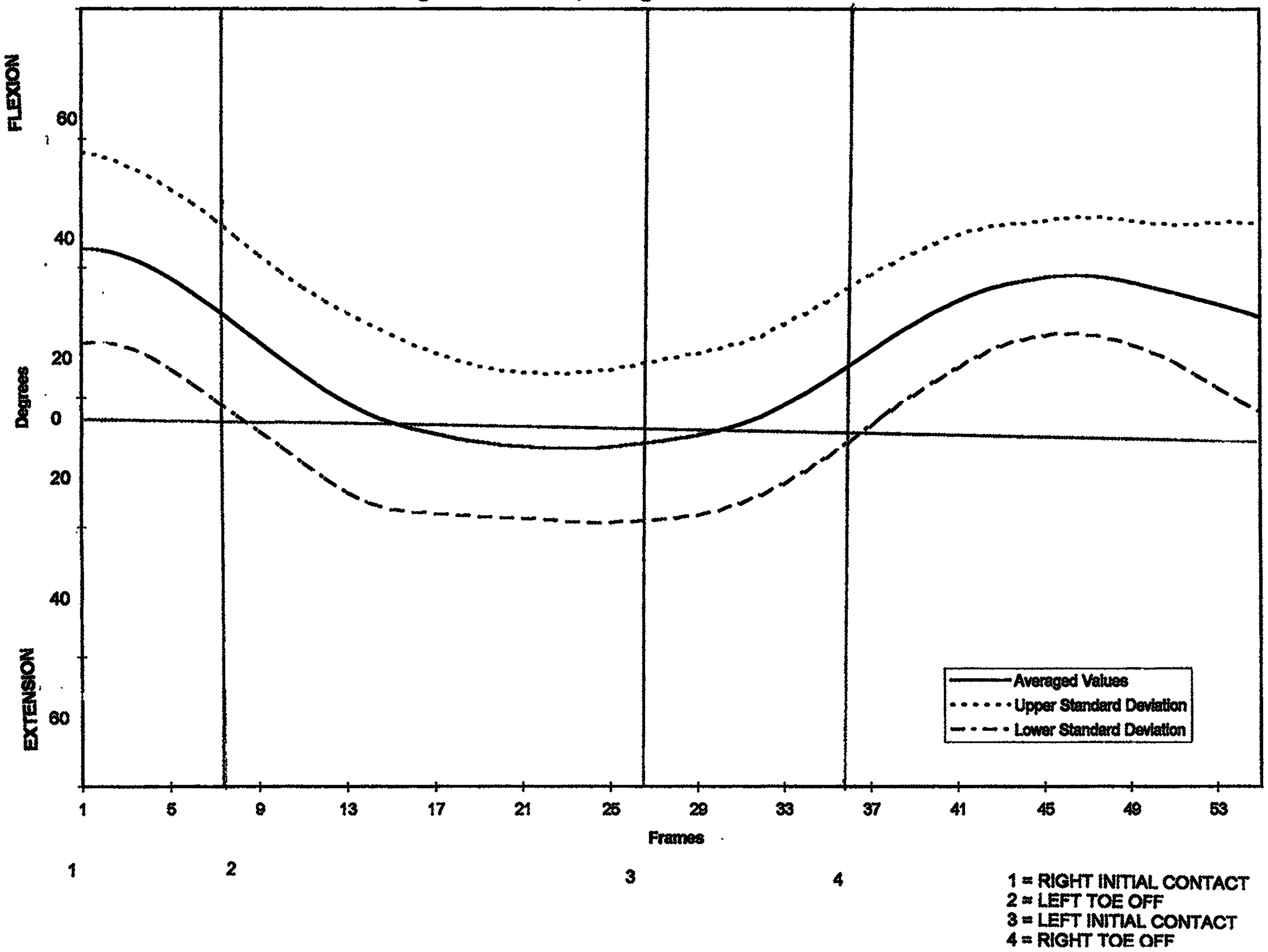


Table 10b.--Averaged Graph of Displacement of Left Hip Flexion and Extension in Normal Children, Ages Four Through Six Years Old, During Gait



able 10c.--Averaged Graph of Displacement of Right Hip Abduction and Adduction in Normal Children, Ages Four Through Six Years Old, During Gait

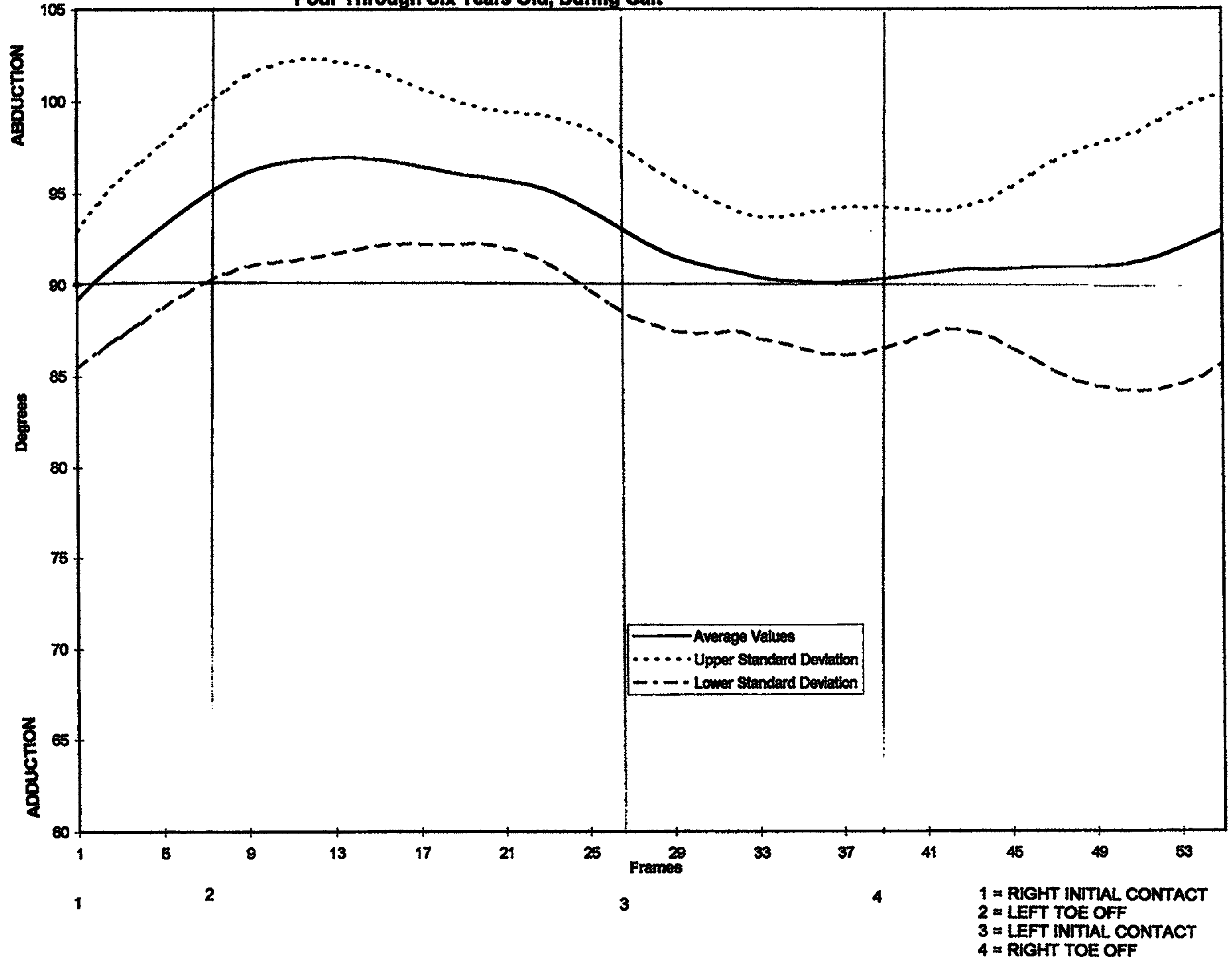


Table 10d.--Averaged Graph of Displacement of Left Hip Abduction and Adduction in Normal Children, Ages Four Through Six Years Old, During Gait

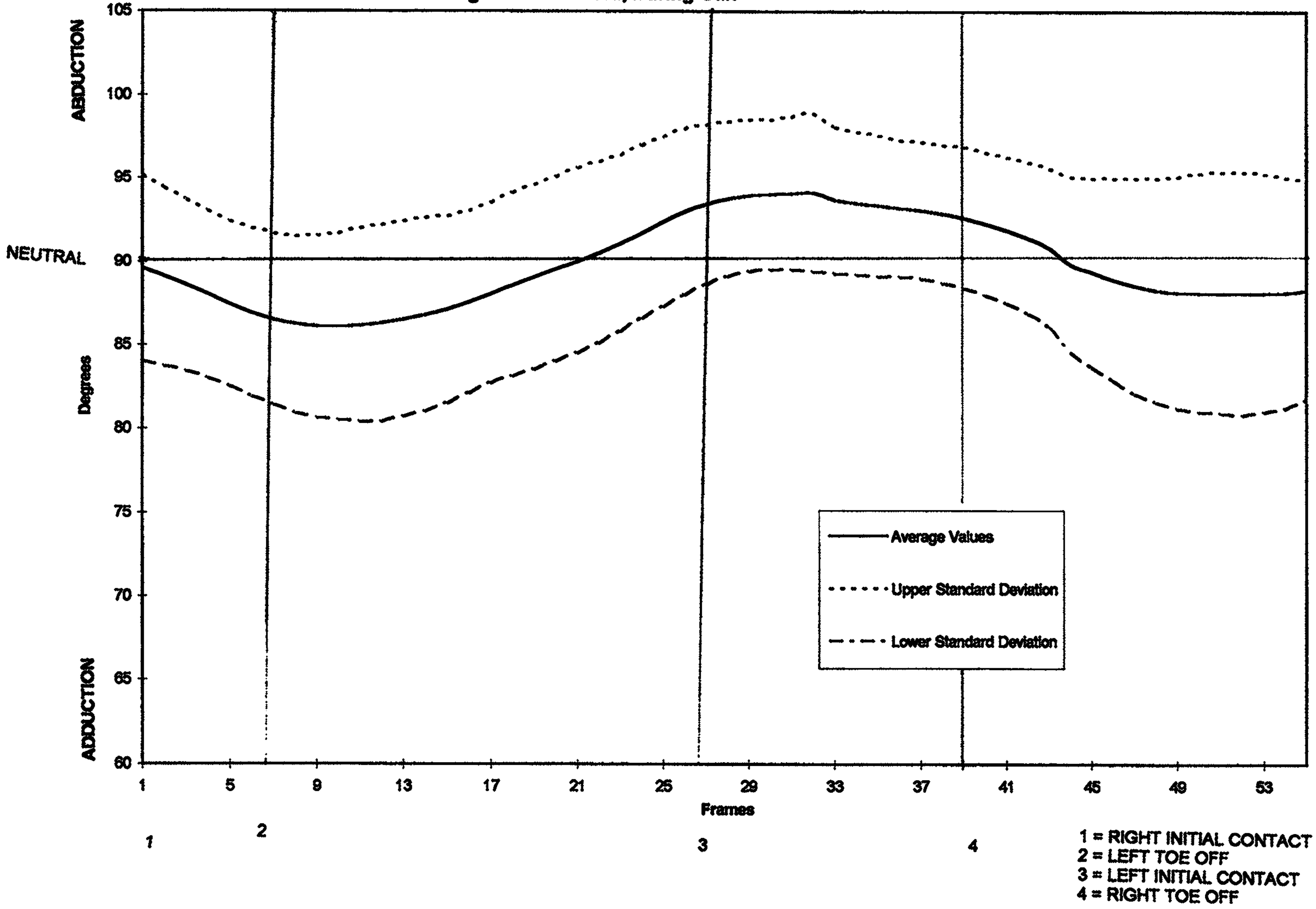


Table 11a.--Averaged Graph of Displacement of Right Knee Flexion and Extension in Normal Children, Ages Four Through Six Year Old, During Gait

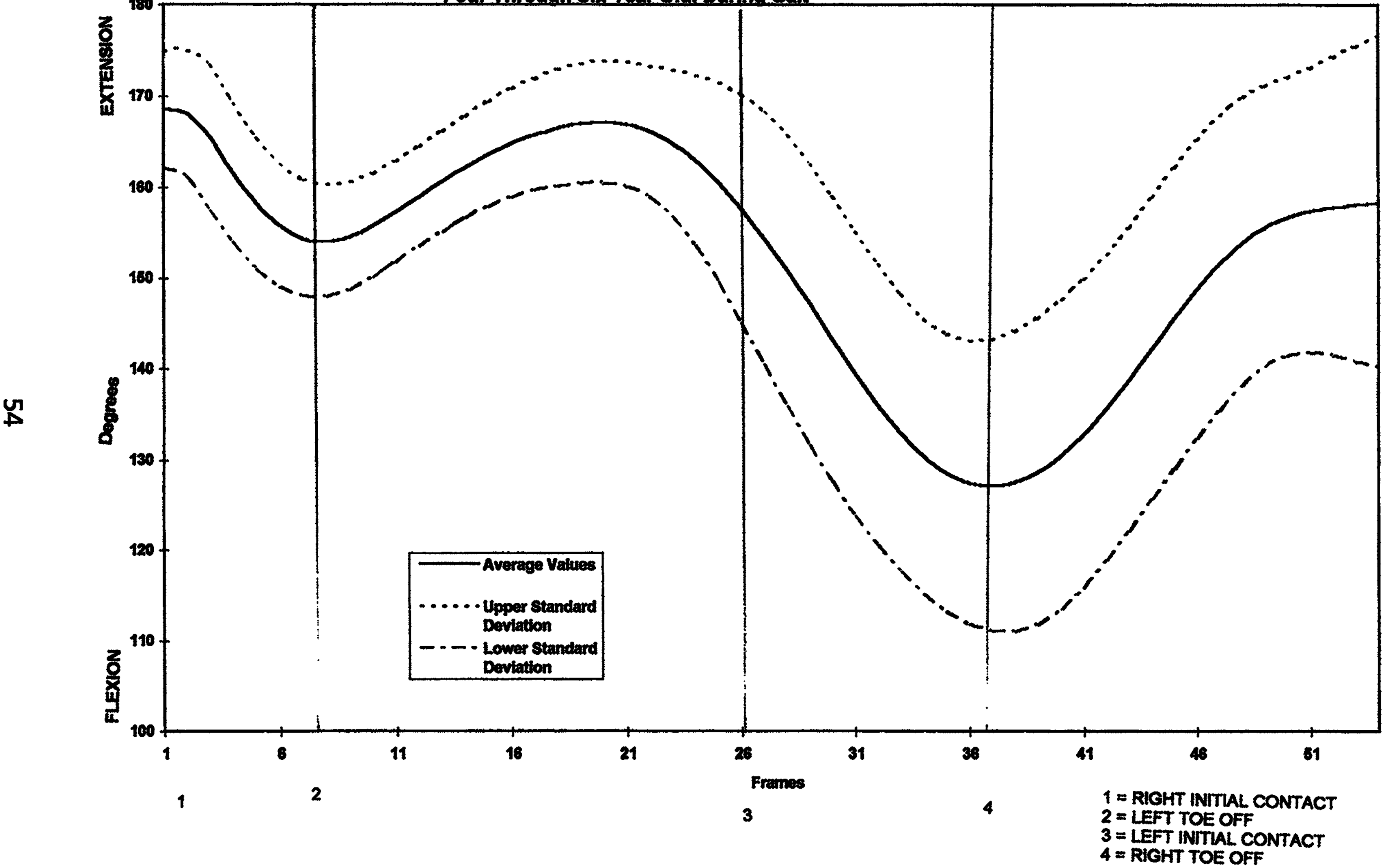


Table 11b.--Averaged Graph of Displacement of Left Knee Flexion and Extension in Normal Children, Ages Four Through Six Year Old, During Gait

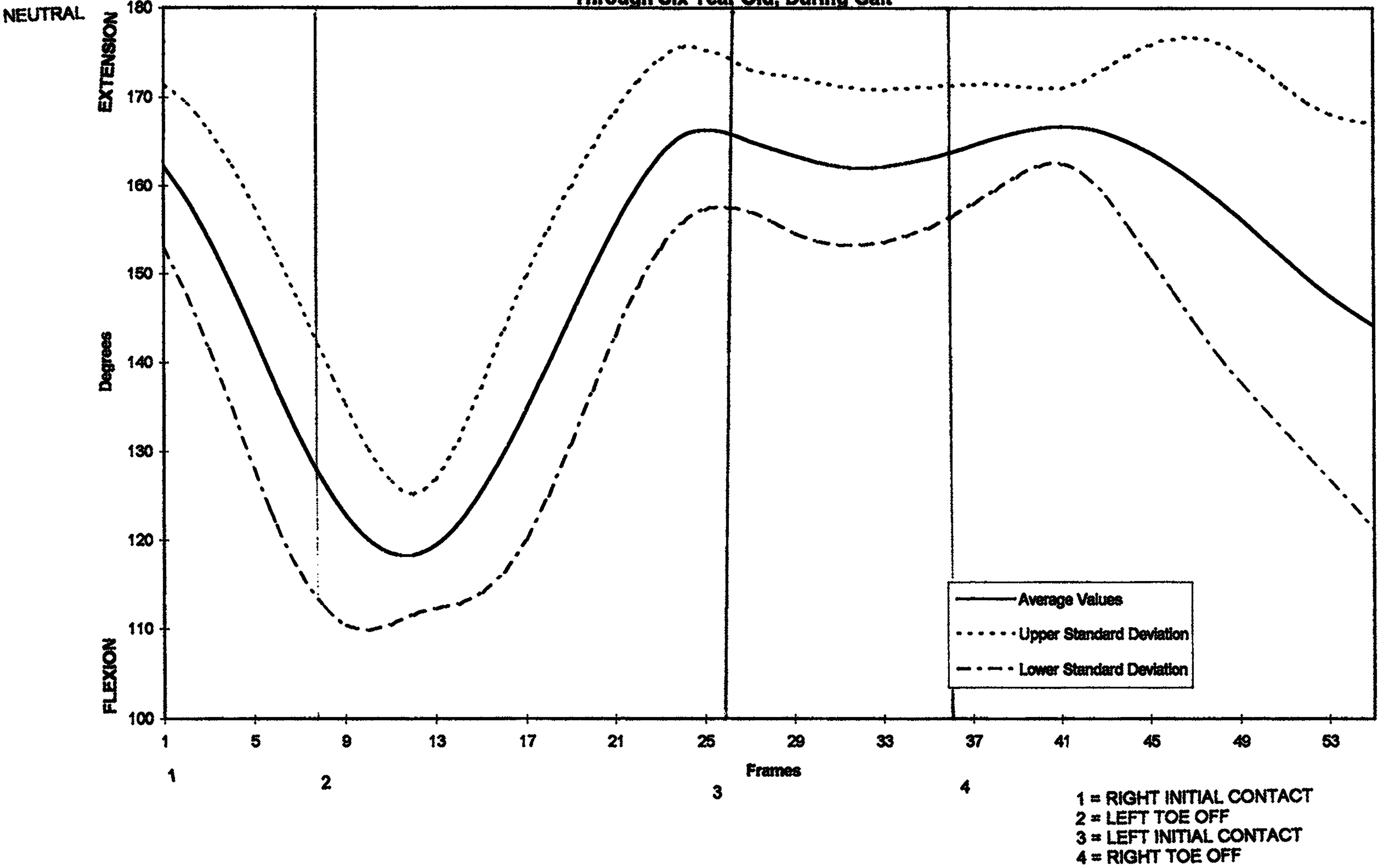


Table 12a.--Averaged Graph of Displacements of Right Ankle Dorsiflexion and Plantarflexion in Normal Children, Ages Four Through Six Years Old, During Gait

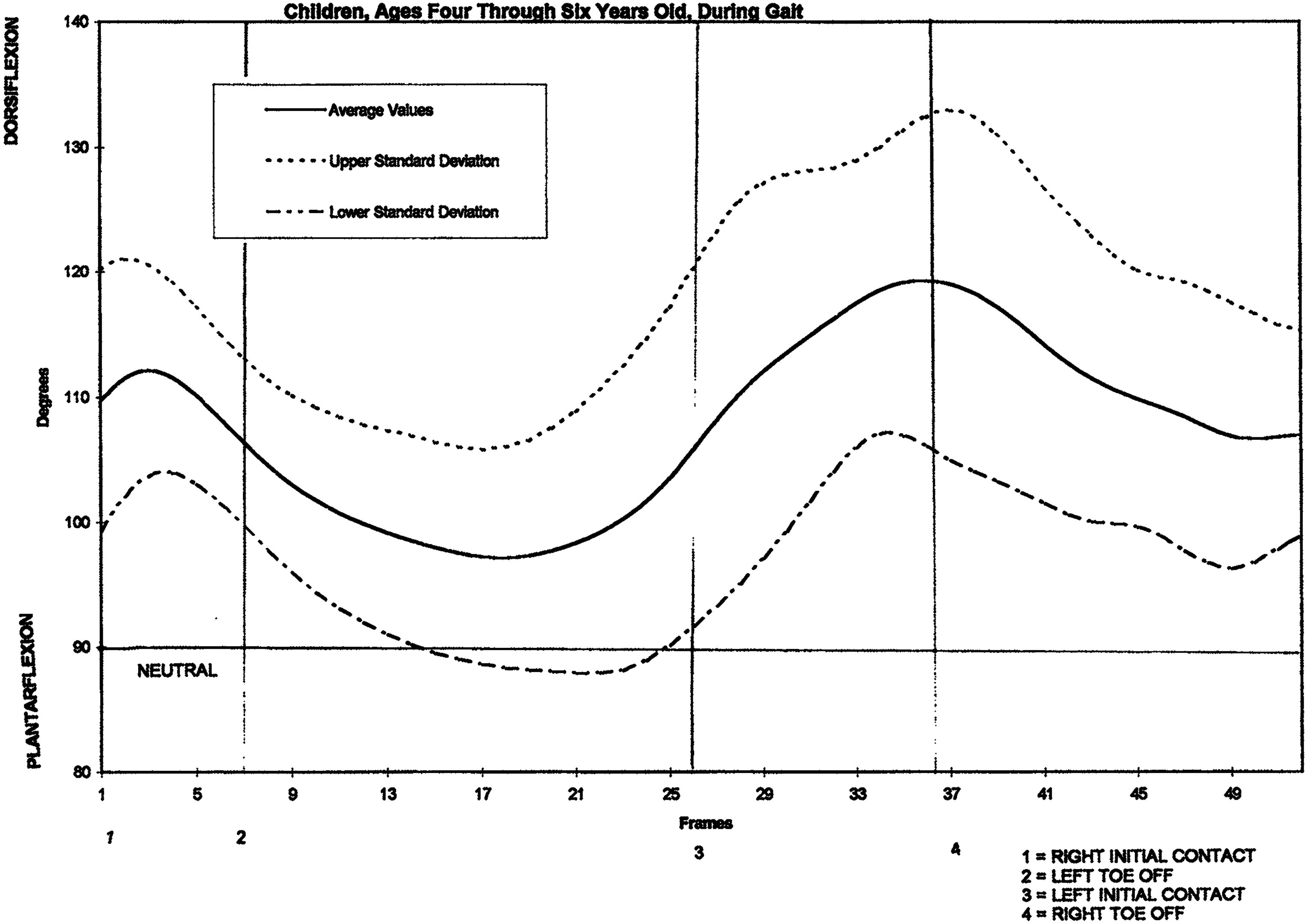
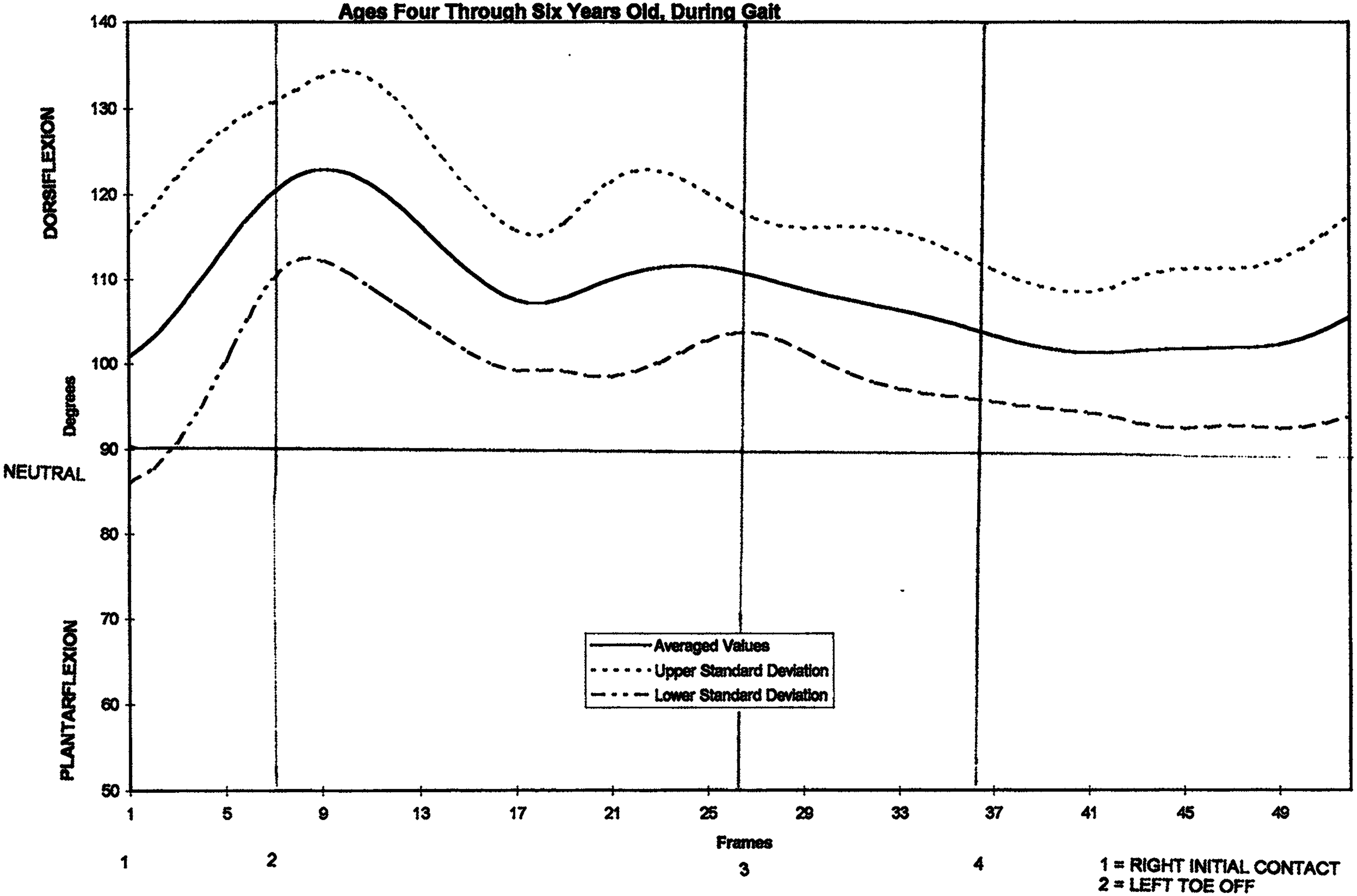


Table 12b.--Averaged Graph of Displacement of Left Ankle Dorsiflexion and Plantarflexion in Normal Children, Ages Four Through Six Years Old, During Gait



1 = RIGHT INITIAL CONTACT
2 = LEFT TOE OFF
3 = LEFT INITIAL CONTACT
4 = RIGHT TOE OFF

Table 13.--Data on Cadence in Normal Children, Ages Four Through Six Years Old

Child	Trial 1		Steps/sec	Trial 2		Steps / sec	Average Steps/ sec
	Time sec	Steps		Time sec	Steps		
1	2	8	4	2	8	4	4
2	4	10	2.5	4	11	2.8	2.65
3	3	7	2.3	3	7	2.3	2.3
4	4	10	2.5	4	11	2.8	2.55
5	4	9	2.3	8	13	1.6	1.95
6	2	6	3	2	8	4	3.5
7	3	9	3	3	9	3	3
8	3	8	2.7	2	7	3.5	3.1
9	3	9	3	3	8	2.7	2.85
10	2	8	4	4	10	2.5	3.25
11	4	10	2.5	4	11	2.8	2.65
12	5	11	2.2	5	11	2.2	2.2
13	5	10	2	4	9	2.3	2.15
14	5	11	2.2	3	8	2.7	2.45
15	4	9	2.3	5	10	2	2.15

Total	= 40.75 steps / sec	
Average	= 2.72 steps / sec	= 163 steps / min
Standard Deviation	= 0.57 steps / sec	= 34.2 steps / min

Table 14.--Summary of Segmental Velocities During the Gait Cycle

	INITIAL DOUBLE LIMB STANCE	SINGLE LIMB STANCE	TERMINAL DOUBLE STANCE	SWING
HIP FLEXION & EXTENSION	SIGNIFICANT INCREASE IN HIP FLEXION VELOCITY	MAXIMUM VELOCITY OF HIP FLEXION OCCURS (100 DEGREES/S DECREASING TO ZERO)	HIP EXTENSION VELOCITY DECREASES	MAXIMUM HIP FLEXION VELOCITY OF 100 DEGREES/S THEN PROGRESSES TO ZERO
HIP ABDUCTION & ADDUCTION	DECREASING HIP ABDUCTION VELOCITY TO 75 DEGREES/SEC	DECREASING ABDUCTION VELOCITY FROM 50 DEGREES/SEC TO ZERO	MAXIMUM ABDUCTION VELOCITY OCCURS TO 40 DEGREES/SEC THEN REACHES NEUTRAL	ABDUCTION VELOCITY INCREASES
KNEE FLEXION & EXTENSION	BEGINS SLIGHTLY FLEXED AND INCREASES TO MAXIMUM KNEE FLEXION VELOCITY OF 220 DEGREES/SESC JUST PRIOR TO SINGLE LIMB STANCE	INCREASED VELOCITY OF KNEE EXTENSION OF 100 DEGREES/SEC OCCURS	KNEE VELOCITY IS MAINTAINED AT 200 DEGREES/SEC	MODERATE INCREASE IN KNEE EXTENSION VELOCITY, REACHING ITS MAXIMUM 200 DEGREES/SEC
ANKLE DORSIFLEXION & PLANTARFLEXION	PROGRESSIVE PLANTARFLEXION VELOCITY, PEAKING JUST PRIOR TO SINGLE LIMB STANCE	INCREASED VELOCITY OF DORSIFLEXION	MAXIMUM PEAK VELOCITY OF DORSIFLEXION REACHED	INCREASED VELOCITY OF PLANTARFLEXION TO SLIGHTLY BEYOND NEUTRAL

Table 15a.--Averaged Graph of Right Hip Flexion and Extension Velocities of Normal Children, Ages Four Through Six Years Old, During Gait

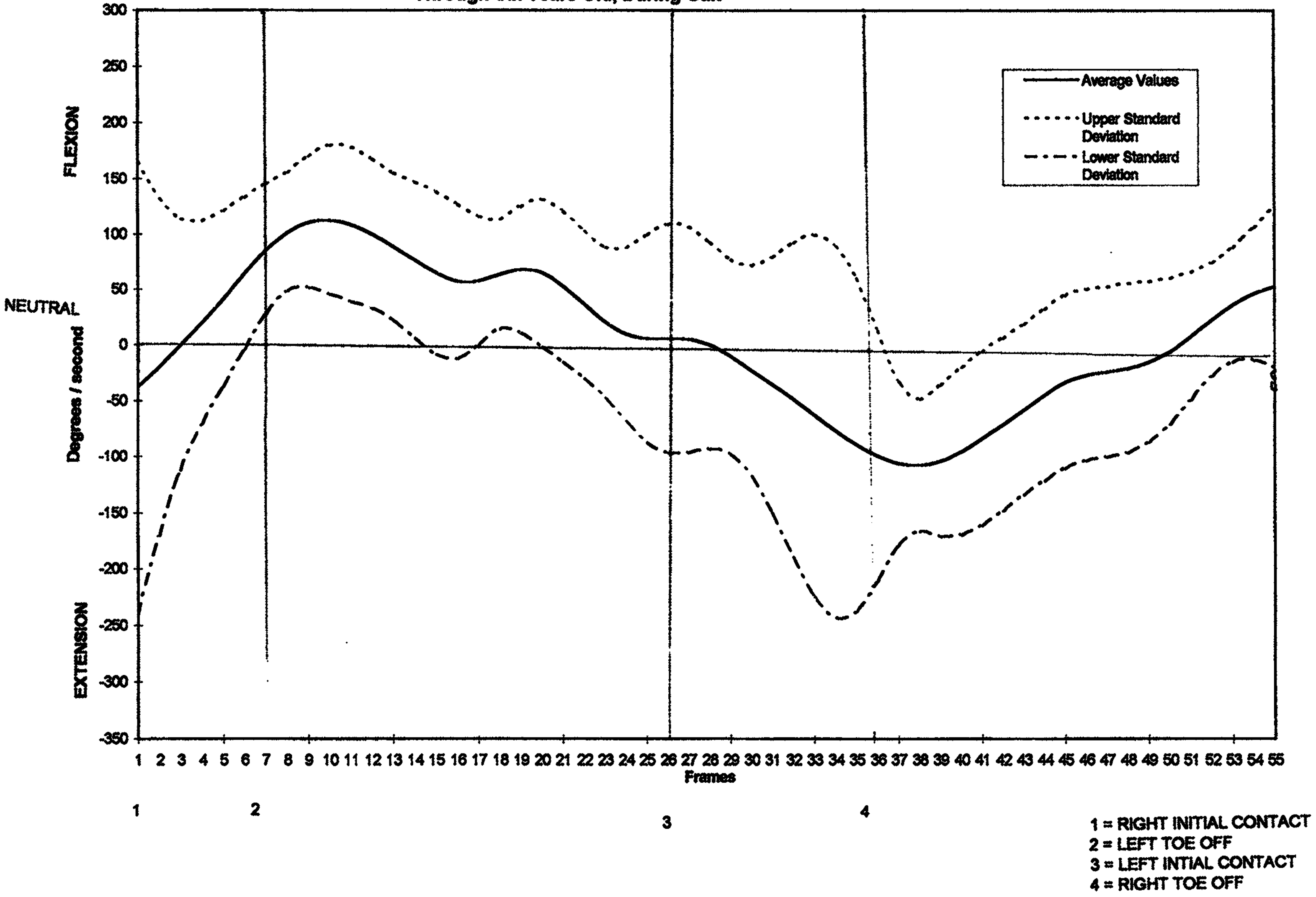


Table 15b.--Averaged Graph of Left Hip Flexion and Extension Velocities of Normal Children, Ages Four Through Six Years Old, During Gait

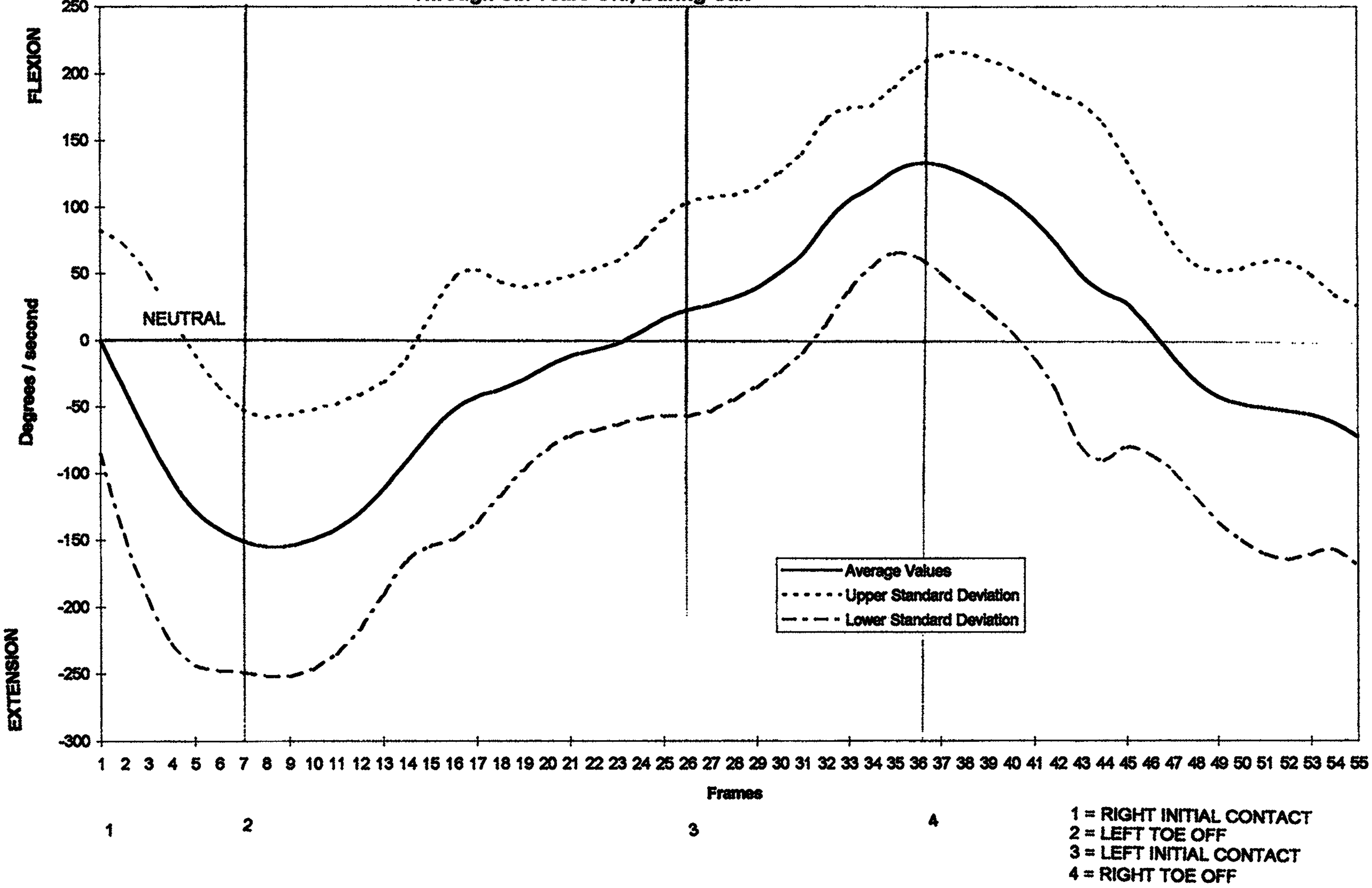


Table 15c.--Averaged Graph of Right Hip Abduction and Adduction Velocities in Normal Children, Ages Four Through Six Years Old, During Gait

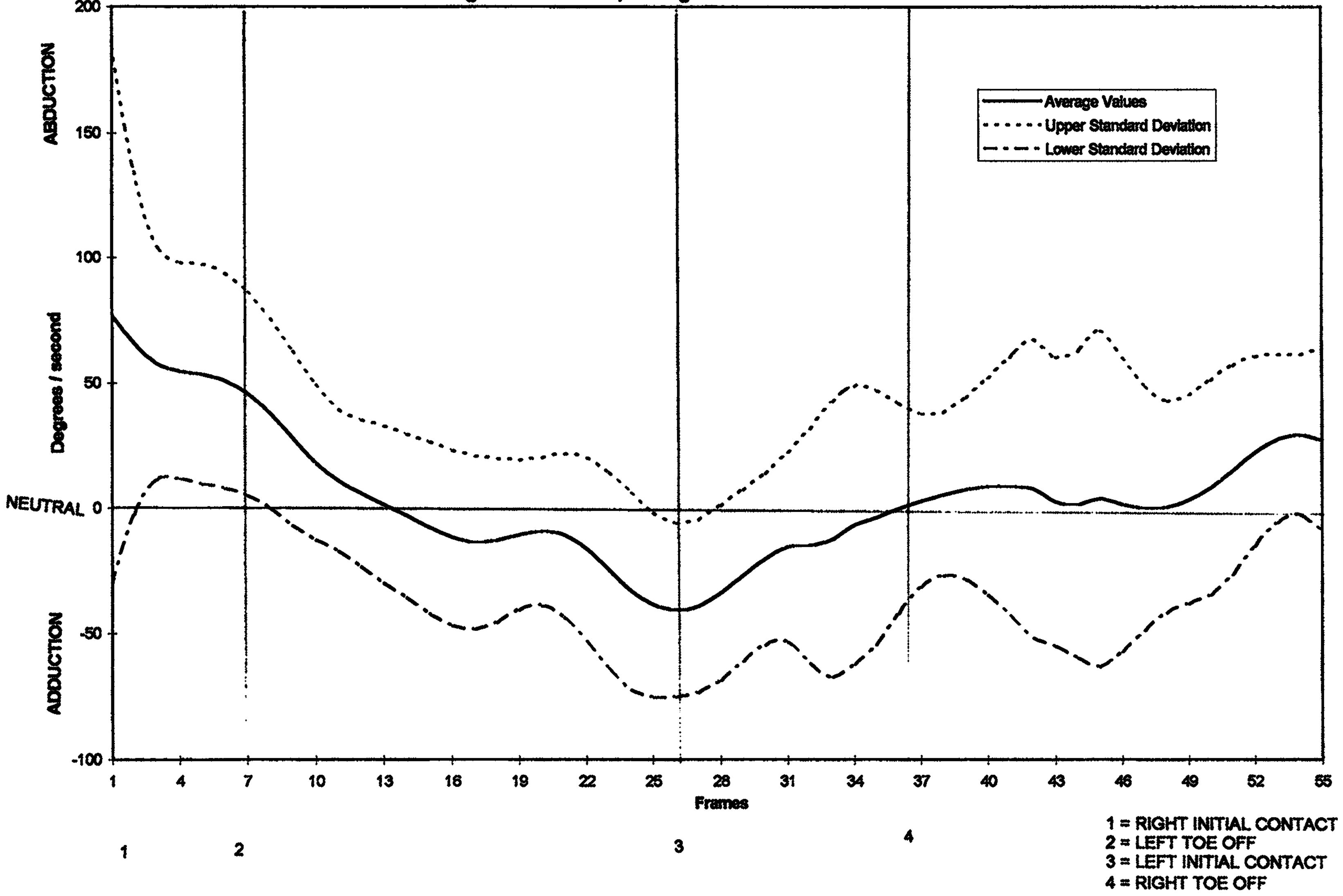
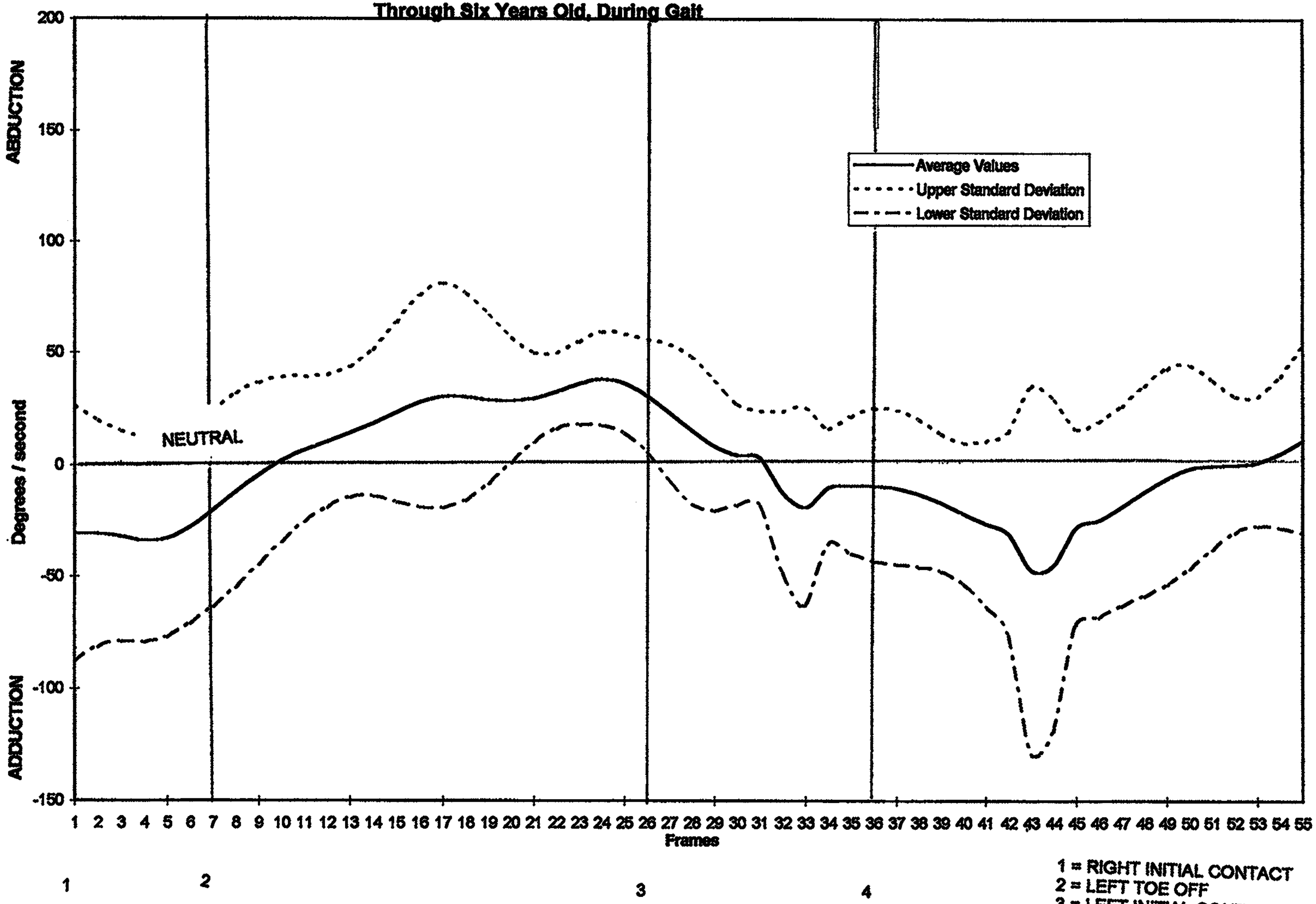


Table 15d.--Averaged Graph of Left Hip Abduction and Adduction Velocities in Normal Children, Ages Four Through Six Years Old, During Gait



1 = RIGHT INITIAL CONTACT
2 = LEFT TOE OFF
3 = LEFT INITIAL CONTACT
4 = RIGHT TOE OFF

Table 15d.--Averaged Graph of Left Hip Abduction and Adduction Velocities in Normal Children, Ages Four Through Six Years Old, During Gait

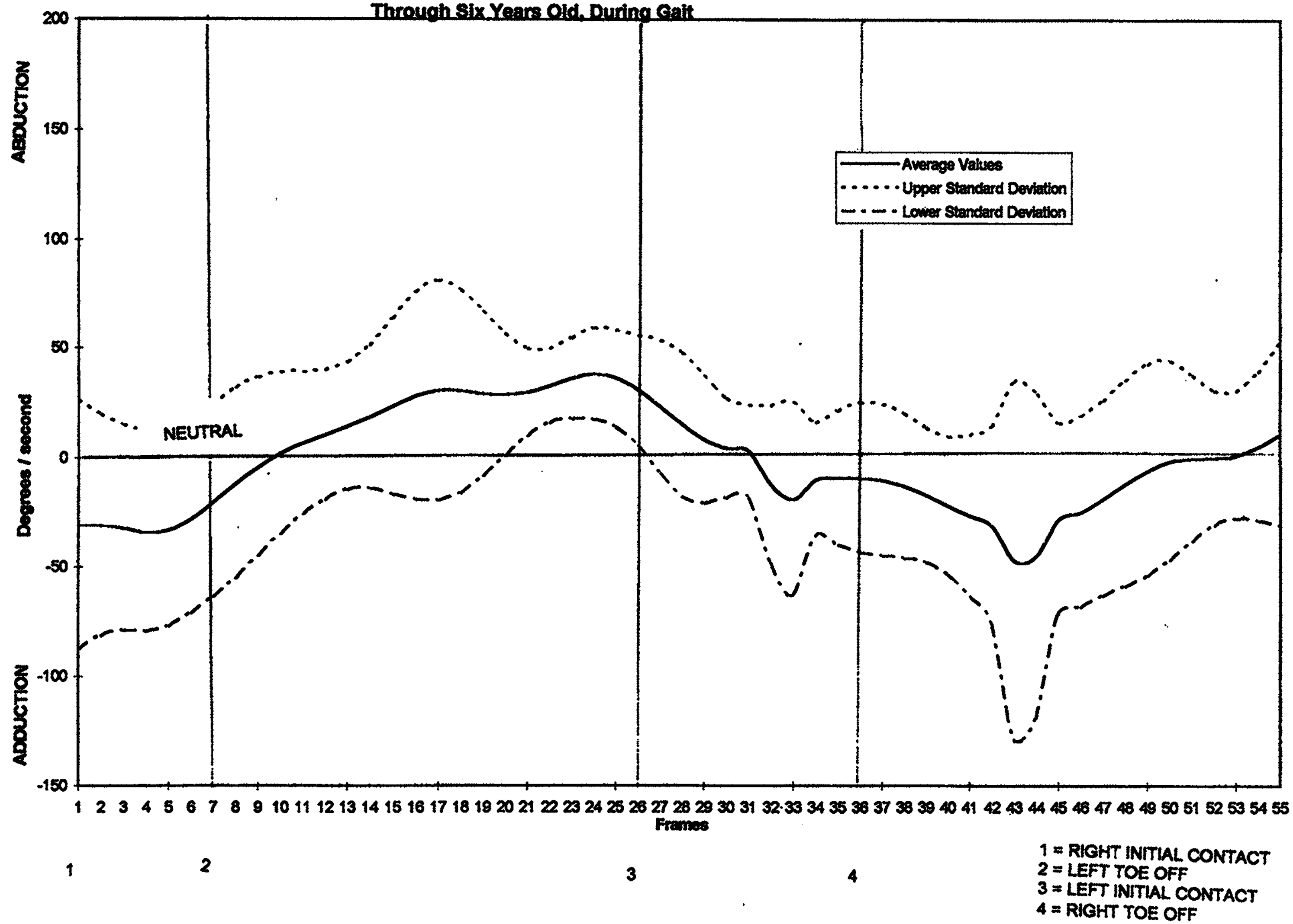


Table 16a.--Averaged Graph of Right Knee Flexion and Extension Velocities of Normal Children, Ages Four Through Six Years Old, During Gait

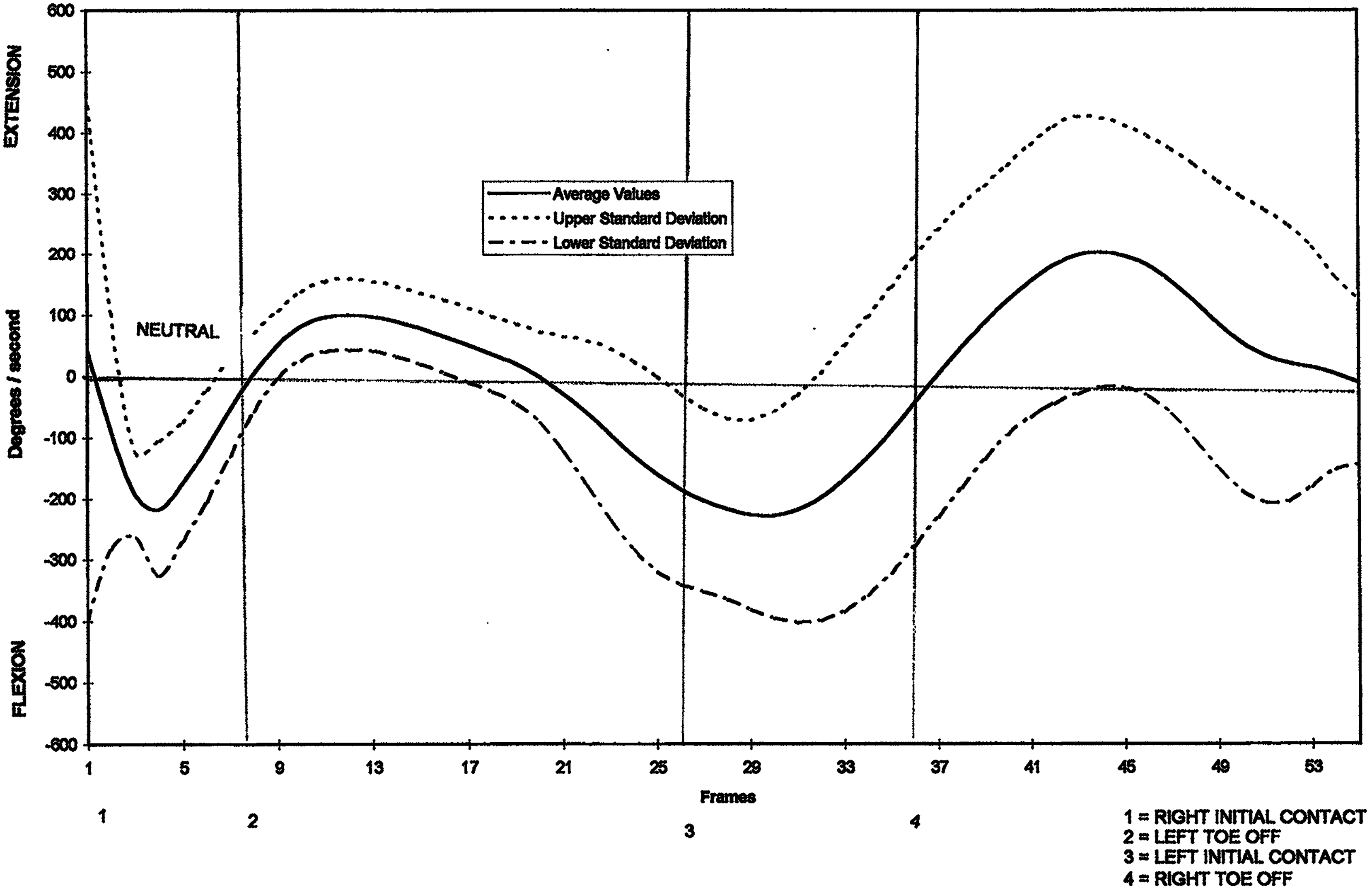


Table 16b.--Averaged Graph of Left Knee Flexion and Extension Velocities in Normal Children, Ages Four Through Six Years Old, During Gait

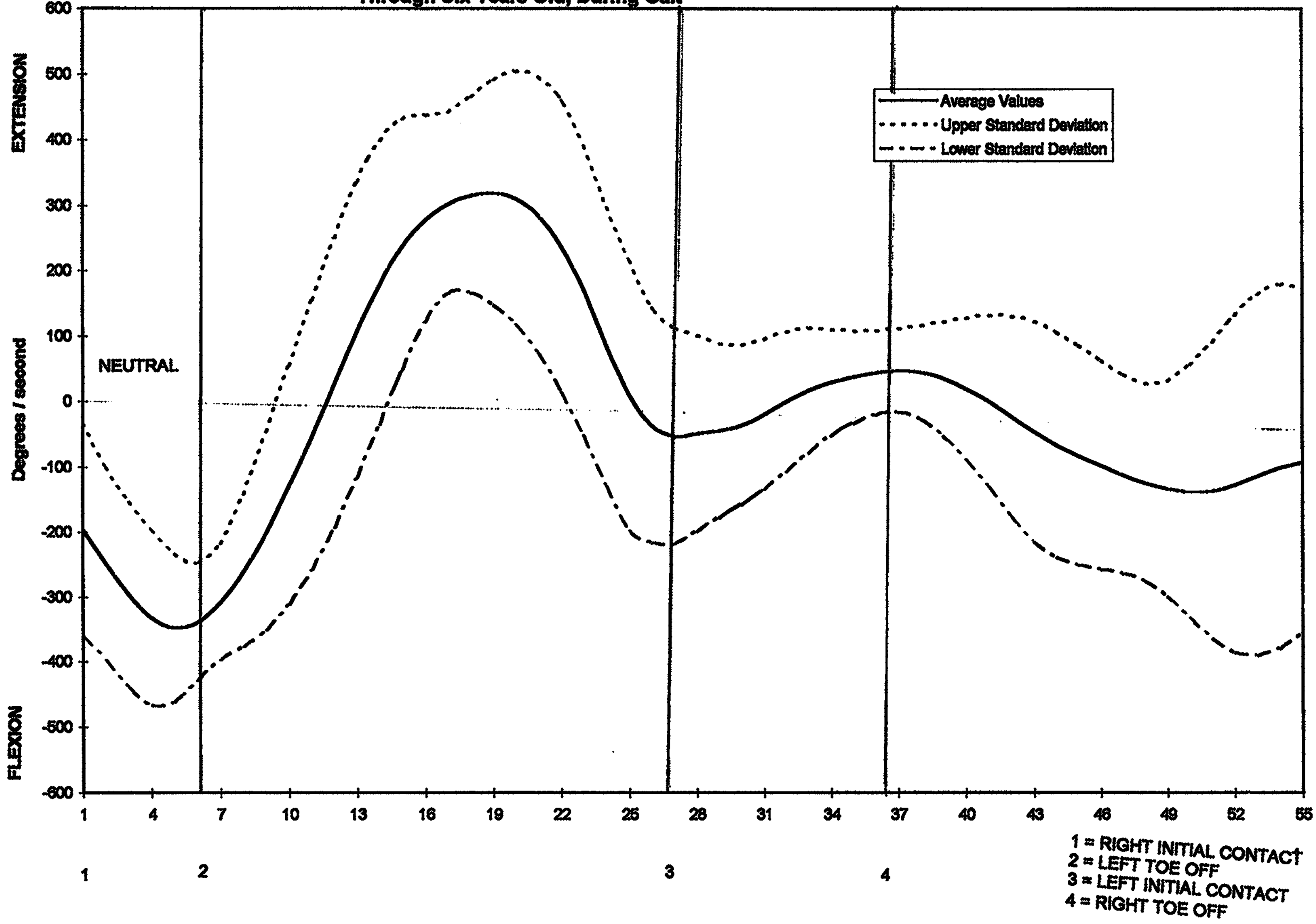


Table 17a.--Averaged Graph of Right Ankle Plantarflexion and Dorsiflexion Velocities in Normal Children, Ages Four Through Six Years Old, During Gait

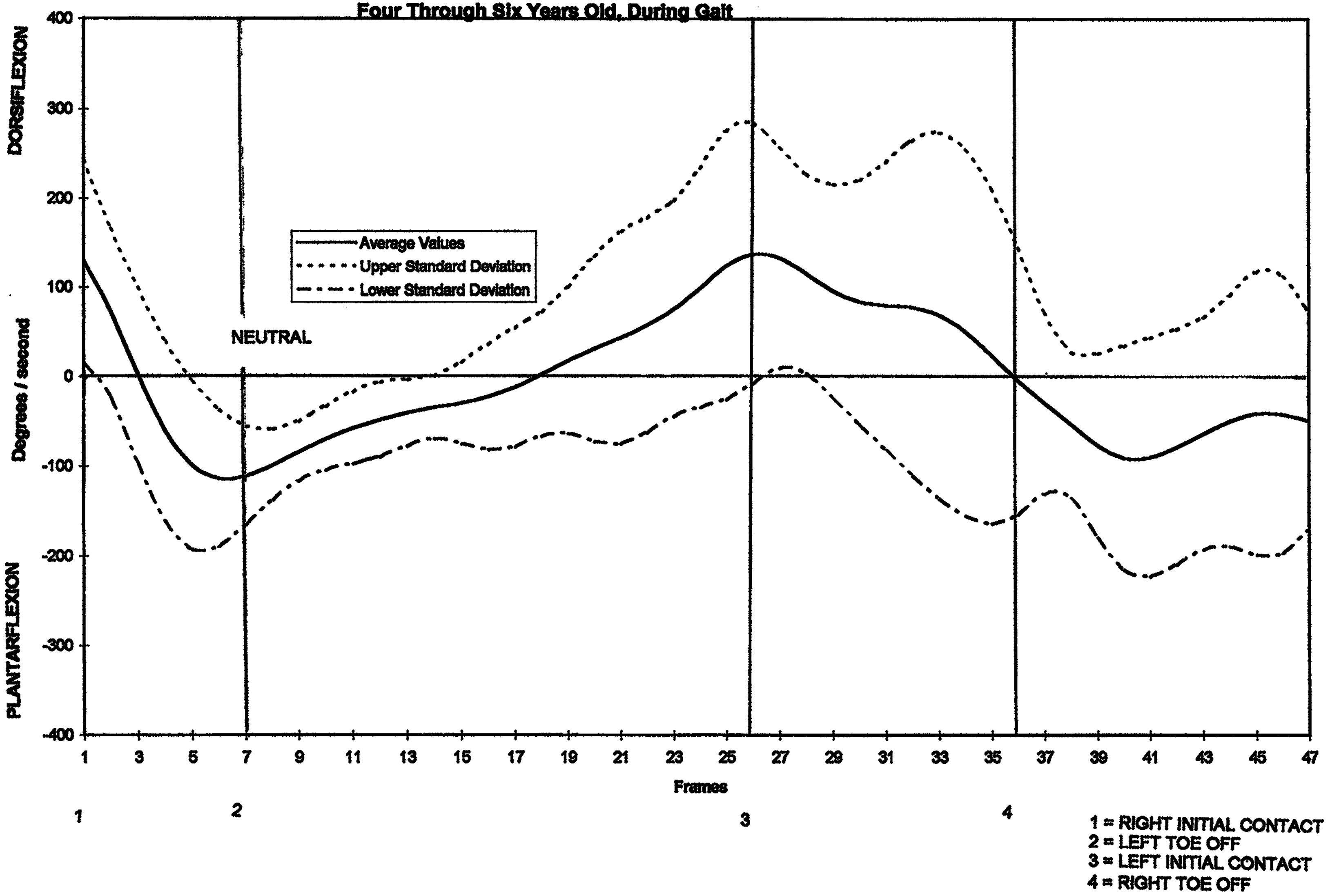
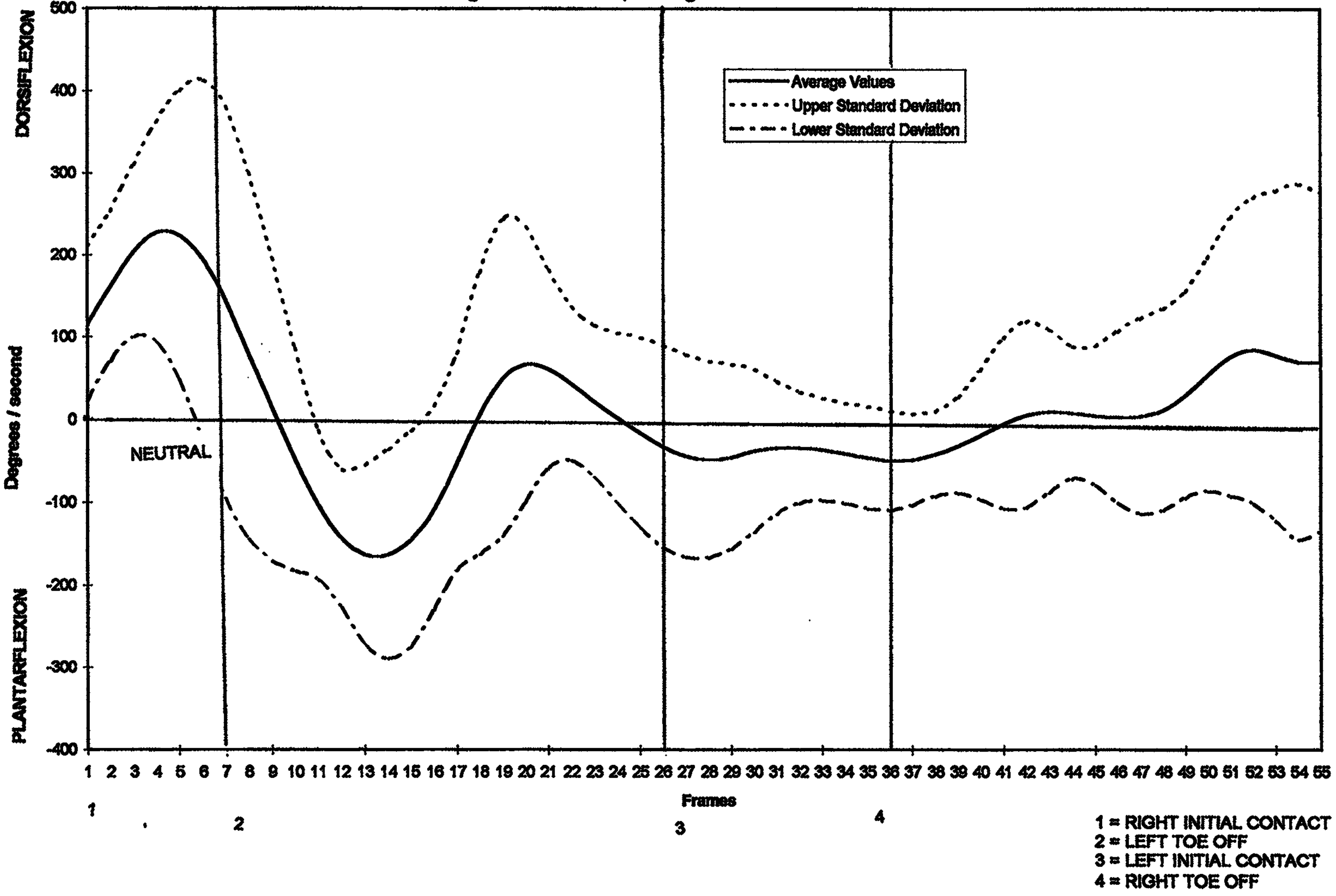


Table 17b.--Averaged Graph of Left Ankle Plantarflexion and Dorsiflexion Velocities in Normal Children, Ages Four Through Six Years Old, During Gait



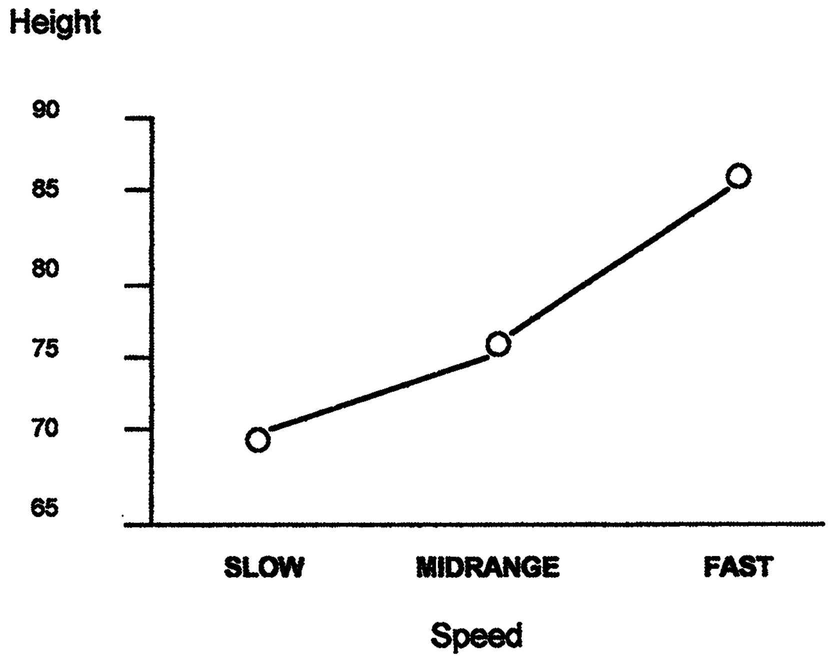
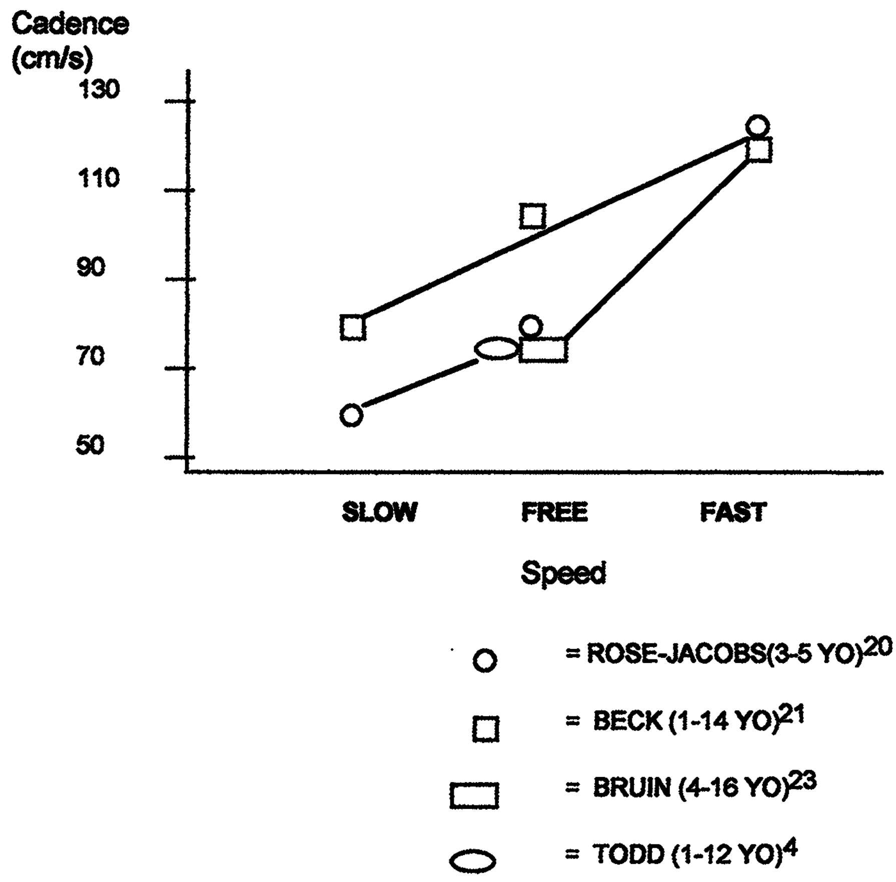


Fig 1.--Stride Length as a Function of Height in Children During Gait at Various Speeds[4]

Fig 2.--Cadence in Children Ages One Through Sixteen Years Old[4,20,21,23]



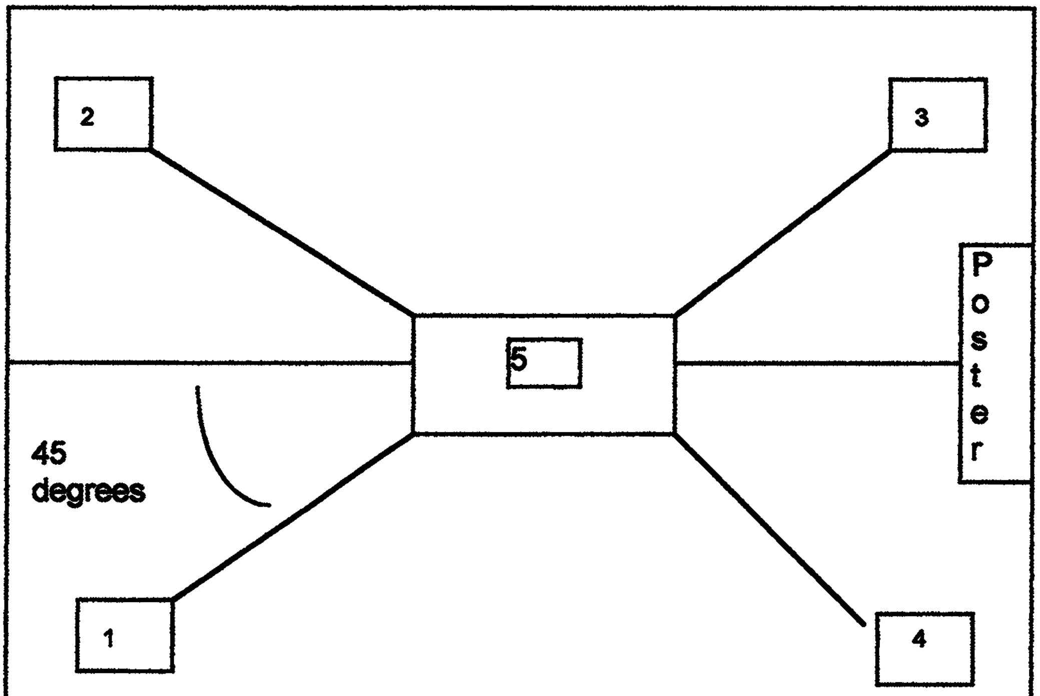


Figure 3.--Diagram of Gait Laboratory at Old Dominion University

Rectangles # 1, 2, 3 and 4 = cameras

Rectangle #5 = calibration zone

Appendix 1.--Operational Definitions & Description of Measurements of Motions of the Pelvis

MOTION	DEFINITION	DESCRIPTION
PELVIC TILT	Movement of the pelvis around the transverse axis of the body.	Measured by joining the line segments created from the bilateral anterior superior iliac spines (ASIS) segments and converging on the marker over the spinal segment of the second sacral vertebra, S2, thus creating a triangle. Neutral position: the position of the triangle parallel to the transverse plane. Anterior pelvic tilt: position of the ASIS markers caudal in reference to the S2 marker Posterior pelvic tilt: position of the ASIS
PELVIC ROTATION	Rotation of the pelvis around the longitudinal axis of the body	Measured by the position of the ASIS marker in relation to the longitudinal axis of the body in the transverse plane. Neutral pelvic rotation: position of the bilateral ASIS markers parallel to each other in the frontal plane Internal pelvic rotation: position of the ASIS marker moving toward the midline External pelvic rotation: position of the ASIS marker moving laterally
PELVIC OBLIQUITY	Movement of the pelvis around the transverse axis	Measured by the position of one ASIS marker in relation to the other ASIS marker Neutral pelvic obliquity: position of bilateral ASIS markers perpendicular to the sagittal plane Superior right pelvic obliquity coincides with inferior pelvic obliquity

Appendix 2.--Operational Definitions & Measurements of Motions of the Hip

MOTION	DEFINITION	DESCRIPTION
HIP FLEXION & EXTENSION sagittal plane	Movement of the femur in reference to the acetabulum in the sagittal plane	Measured by converging the line segments of the ASIS markers to the greater trochanteric markers and the greater trochanteric markers to the lateral condylar markers; the vertex of the angle will be the hip joint. In using this technique, the computer will yield a certain amount of flexion when the subject stands in neutral. The angle created will be subtracted from the raw data to yield a derived measurement. Zero degrees of hip flexion and extension: the position of the femur at a ninety degree angle from the line segment of the bilateral ASIS
HIP ABDUCTION & ADDUCTION frontal plane	Movement of the femur in reference to the acetabulum in the frontal plane	Measured by creating an angle between the line segment of the bilateral ASIS markers and the line segment of the markers of the greater trochanter to the lateral condyle; the vertex of the angle will reflect the hip joint motions Zero degrees of abduction and adduction: position of the femur perpendicular to the plane of the ASIS
HIP ROTATION transverse plane	Movement of the femur in the acetabulum around the longitudinal axis of the femur	Measured using a ten centimeter wand with markers at its base and tip; held to the midshaft of the thigh with a velcro band. The line segment of the base to the tip of the wand in reference to the line segment of the greater trochanter to the lateral condyle will yield the degrees of hip rotation. Neutral rotation : position of the line segment comprised of the wand markers parallel to the sagittal plane. Internal hip rotation: position of the line segment of the wand moving laterally External hip rotation: position of the line segment of the wand moving medially

Appendix 3.--Operational Definitions & Measurements of Motions of the Knee and Ankle

MOTION	DEFINITION	DESCRIPTION
KNEE FLEXION & EXTENSION sagittal plane	Movement of the tibia in relation to the femur around the knee joint axis	Measured by the intersection of the line segments of the greater trochanter to the lateral condylar markers and the lateral condylar markers to the lateral malleolar markers; the vertex of the angle will reflect knee joint motions Zero degrees of knee flexion and extension: position of the markers of the greater trochanter, lateral condyle and lateral malleolus are in a straight line Any hyperextension of the knee will be that beyond the zero point and will be designated by a negative number
TIBIAL ROTATION transverse plane	Movement of the tibia around the vertical axis of the tibia	Measured by using a ten centimeter wand with markers at its base and tip, held to the midshaft of the tibia with a velcro band Neutral rotation: position of the line segment of the wand's markers perpendicular to the frontal plane Internal rotation: position of the tibial wand approaching the midline External rotation: position of the wand moving away from midline
ANKLE DORSI-FLEXION & PLANTAR-FLEXION sagittal plane	Movement of the foot in relation to the tibia around the ankle joint axis	Measured by the intersection of the line segments of the lateral condylar marker to the lateral malleolar marker and the lateral malleolar marker to the marker of the base of the fifth metatarsal The angle will yield a certain degree of plantarflexion and will be subtracted from the raw data to provide a derived measure for dorsiflexion and plantarflexion