THE VALUE OF NORMATIVE DATA IN GAIT ANALYSIS

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The term pathological gait has little meaning divorced from normal gait. The significance of the measurements carried out in gait laboratories depends upon, (a) the accuracy of these measurements, (b) the existence of reliable normal controls and, last but not least, proper understanding of the human control system and the muscle forces producing movement. In the development of reliable control standards the largest holes in our knowledge are in the very young and the very old.

Our movement measurement system using three dimensional triangulation measurements from movie film was first presented in 1967 in a scientific exhibit at the American Academy of Orthopedic Surgeons annual meeting. Since that time we have added many additional measurements, and data reduction time has been greatly reduced. At this time an average study generates twelve angular joint rotations for each lower extremity, five force curves, four to eight electromyograms and twenty linear measurements.

To verify the repeatability of the measurement system used in the gait laboratory; two different observers read the same walk cycle two times each. The results of this test appear in the graphs (Figs. 1 & 2). The circle and square are the results from the first observer and the triangle and asterisk are the measurements of the second observer.

I am going to show some preliminary results from our studies of normal children one to seven years of age, then present summaries of gait studies of three children with pathological gait. These normal and pathological studies are presented to show our dependence upon normative data for any description of pathological gait and to emphasize the great need at this time for more complete normal control data.

NORMAL GAIT

Case Study - C.S.

This normal one year old girl walks in a staccato manner (Fig. 3). The walking cadence is rapid, but the steps are very short. Walking velocity is approximately one half that of an average adult. The elbows are maintained in flexion and reciprocal arm movements are not yet present. In the frontal plane a wide base of support can be observed. Foot strike occurs without initial heel strike.

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General Measurements

	Right	Left
Opp. toe off (% cycle)	12	16
Opp. foot strike (% cycle)	50	48
Single stance (% cycle)	38	32
Toe off (% cycle)	66	61
Step length (cm)	21	21
Stride length (cm)	42	42
Cycle time (sec)	.7	.7
Cadence (steps/min)	171	171
Walking velocity (cm/sec)	60	60
(m/min)	36	36

By comparison with a composite of normal adult controls there is increased swing phase hip (Fig. 4B) and knee Flexion (Fig. 4C). Plantar flexion is present at foot strike, and there is impaired dorsiflexion in early swing phase (Fig. 4D). There is excessive external rotation of pelvis (Fig. 4E), femur (Fig. 4F), tibia (Fig. 4G), and foot (Fig. 4H) in both stance and swing phase.

All of these variations from mature gait are normal initial adaptations to the demands of independent walking.

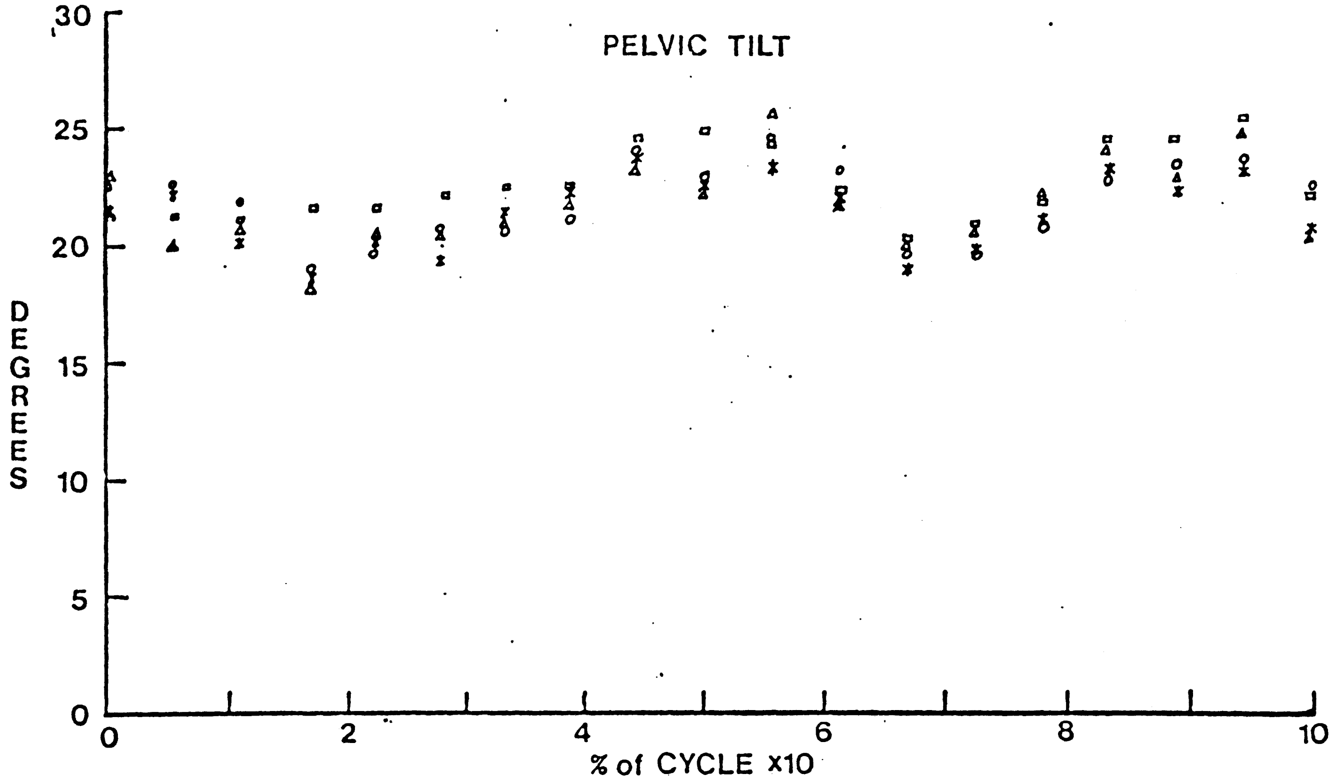
Case Study - R.K.

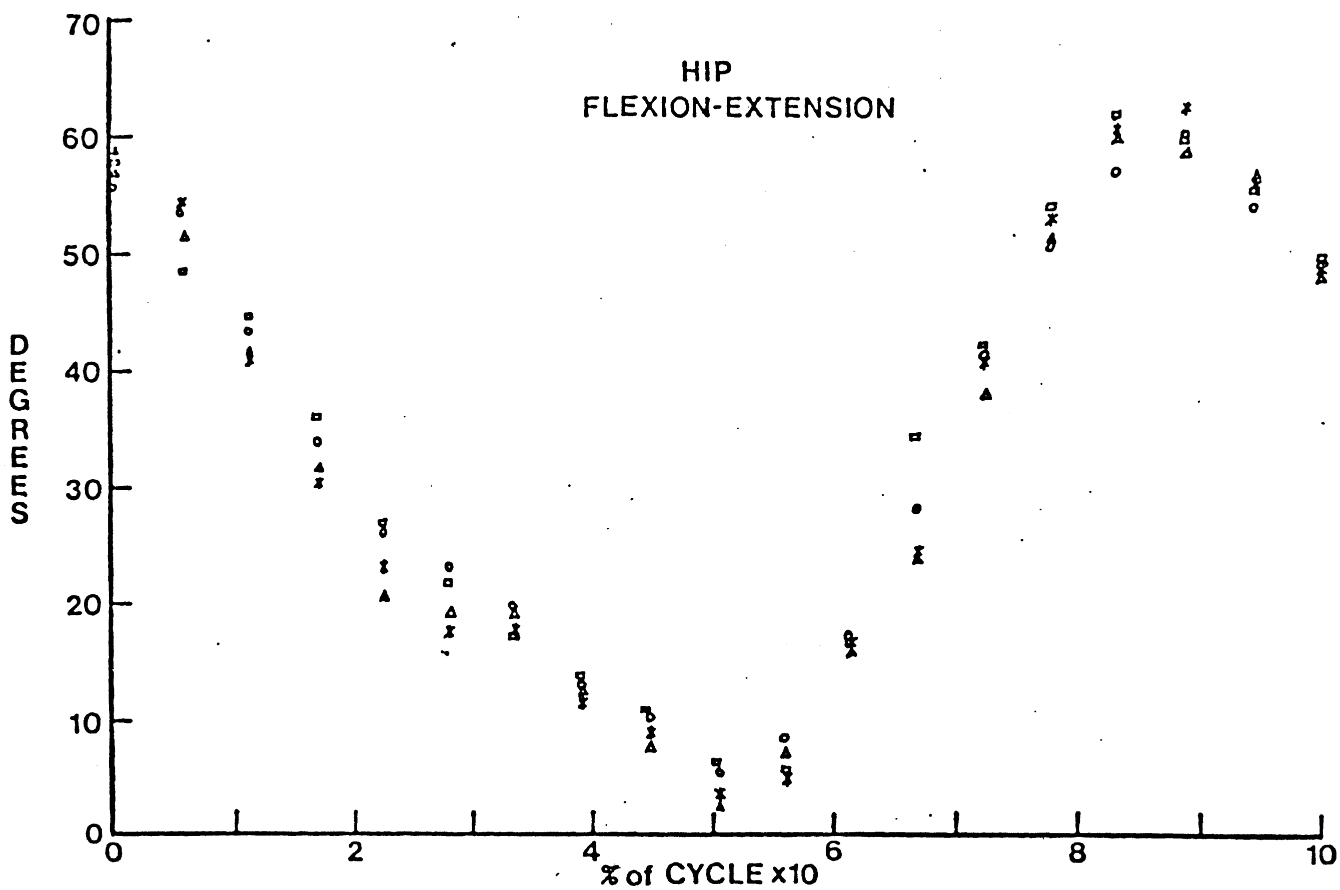
This normal three year old male demonstrates nearly mature gait (Fig. 5). Reciprocal arm movements are present. The dynamic base of support is normal. By comparison with the normal one year old girl, cadence is slower and walking velocity is greater. Limitation of step length still prevents achievement of mature gait walking velocity.

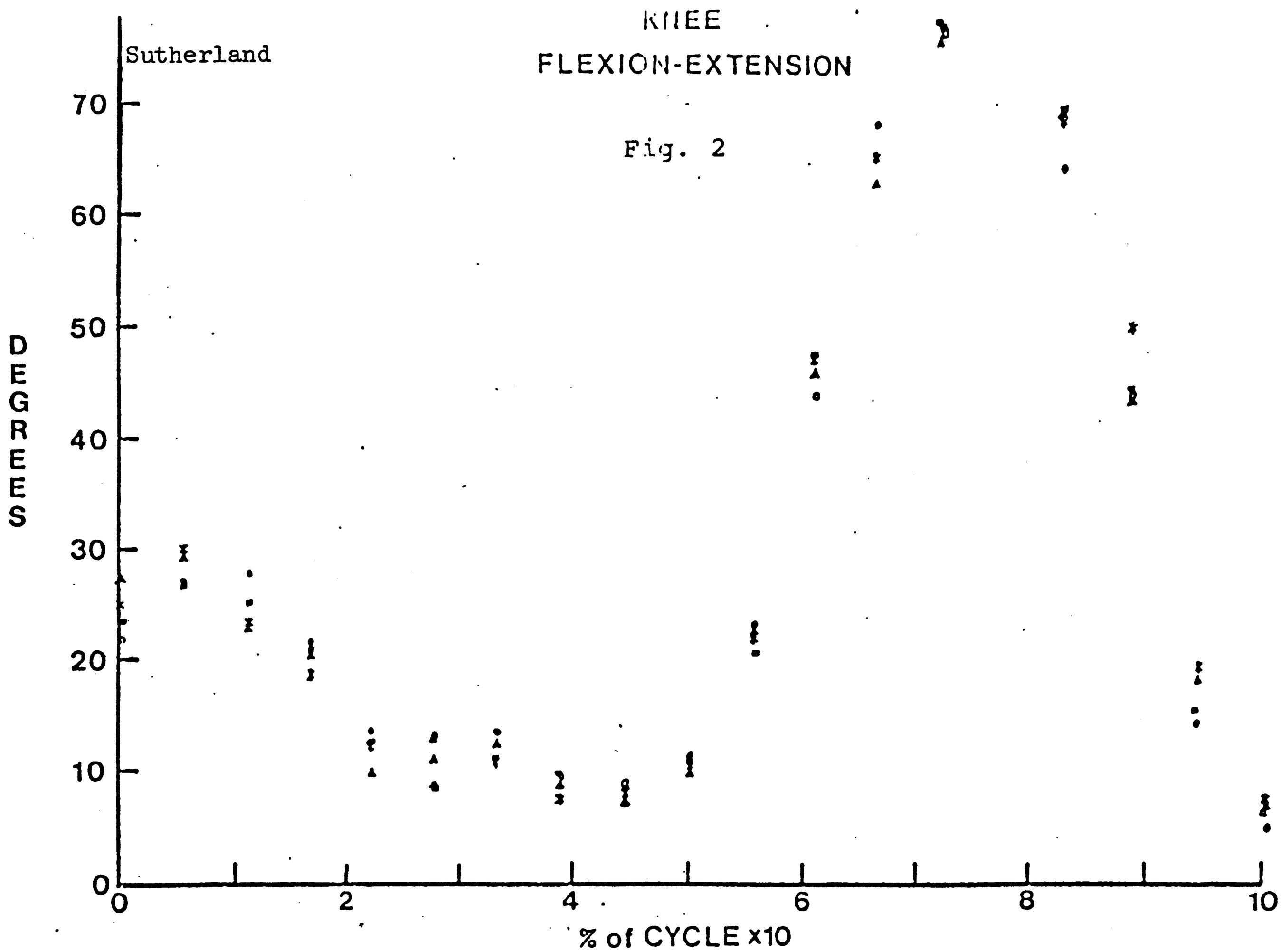
General Measurements

	Right	Left
Opp. toe off (% cycle)	18	17
Opp. foot strike (% cycle)	52	49
Single stance (% cycle)	34	32
Toe off (% cycle)	68	67
Step length (cm)	29	32
Strike length (cm)	61	61
Cycle time (sec)	.76	.76
Cadence (steps/min)	158	158
Walking velocity (cm/sec)	80	80
(m/min)	48	48

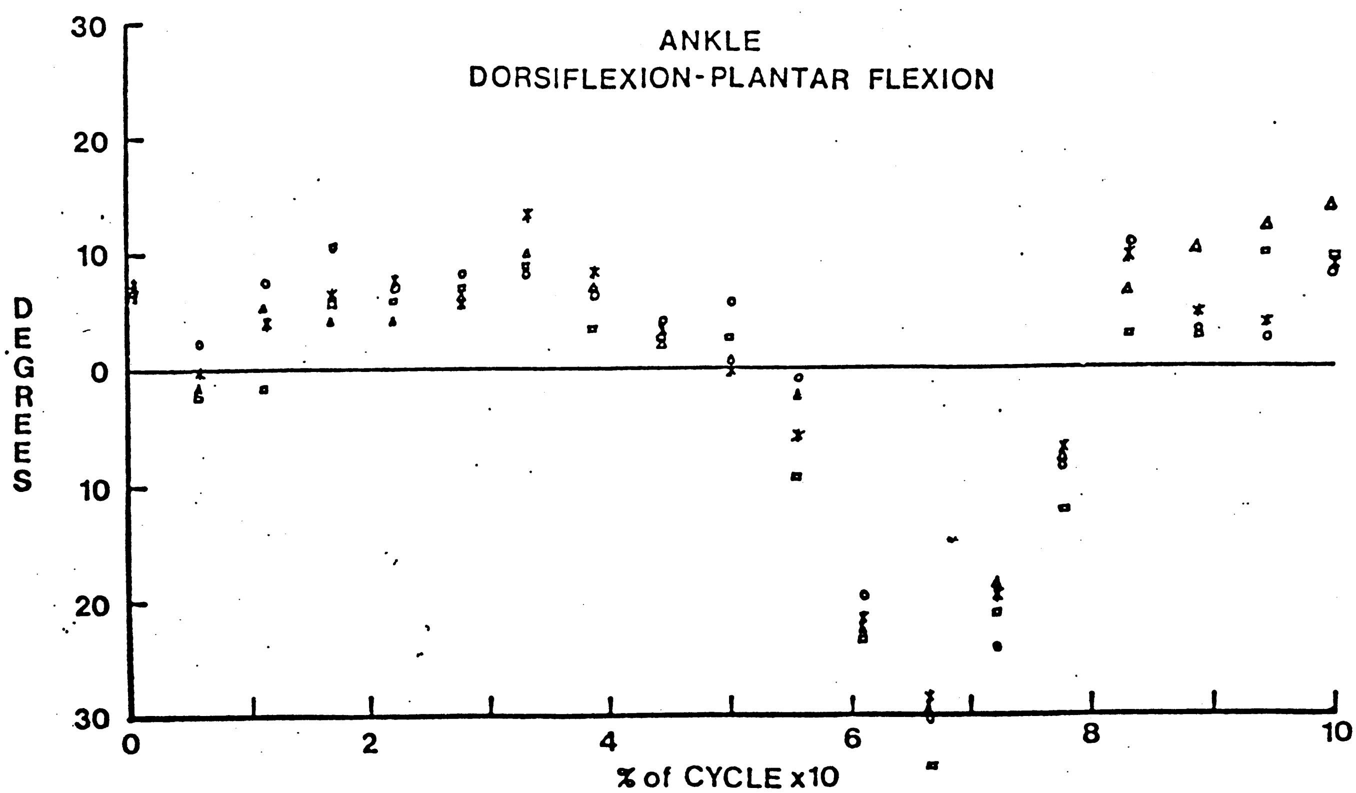
Fig. 1


PELVIC TILT
30
25
20
15
10
5
0
DEGREES
0
2
4
6
8
10
% of CYCLE x10


HIP
FLEXION-EXTENSION
70
60
50
40
30
20
10
0
DEGREES
0
2
4
6
8
10
% of CYCLE x10

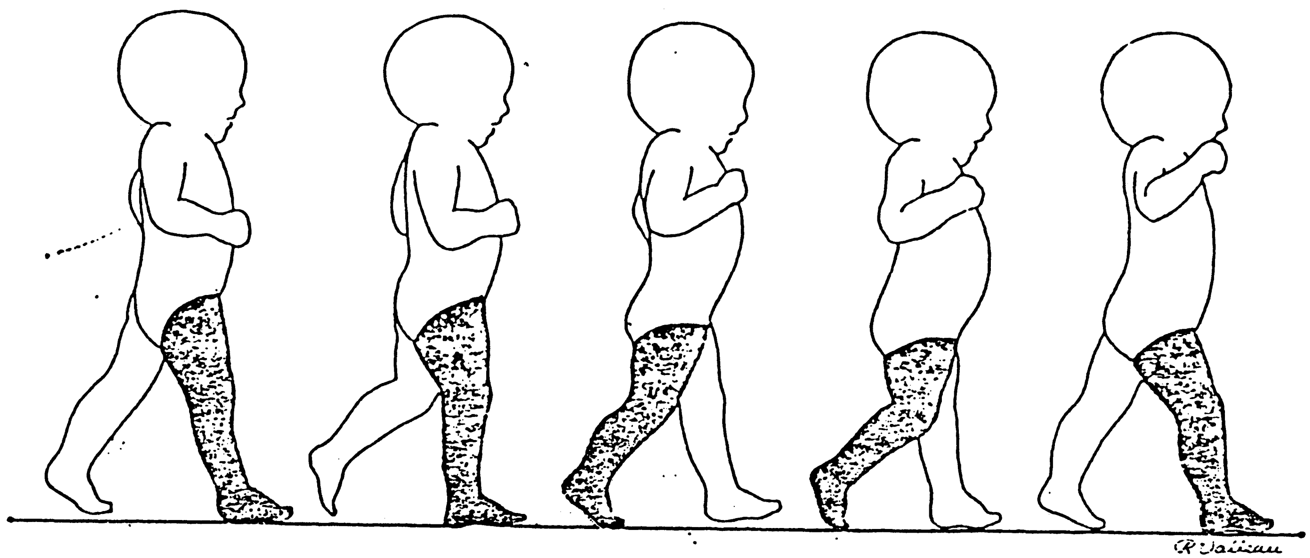


Sutherland
KNEE
FLEXION-EXTENSION
Fig. 2
DEGREES
70
60
50
40
30
20
10
0
0
2
4
6
8
10
% of CYCLE x10



ANKLE
DORSIFLEXION-PLANTAR FLEXION
DEGREES
30
20
10
0
10
20
30
0
2
4
6
8
10
% of CYCLE x10

Fig. 3



NORMAL 1 YEAR OLD

Note the flexed elbows, absent arm swing, plantar flexion at foot strike and increased shoulder sway in this one year old girl.

Fig. 4
Joint Angular Rotations

A. Slightly increased sagittal plane pelvic oscillation in this normal one year old girl.

B. Increased swing phase hip flexion.

C. Extended knee throughout stance.

D. Plantar flexion at foot strike and drop foot in swing.

E to H. Exaggerated external rotation of pelvis, femur, tibia and foot.

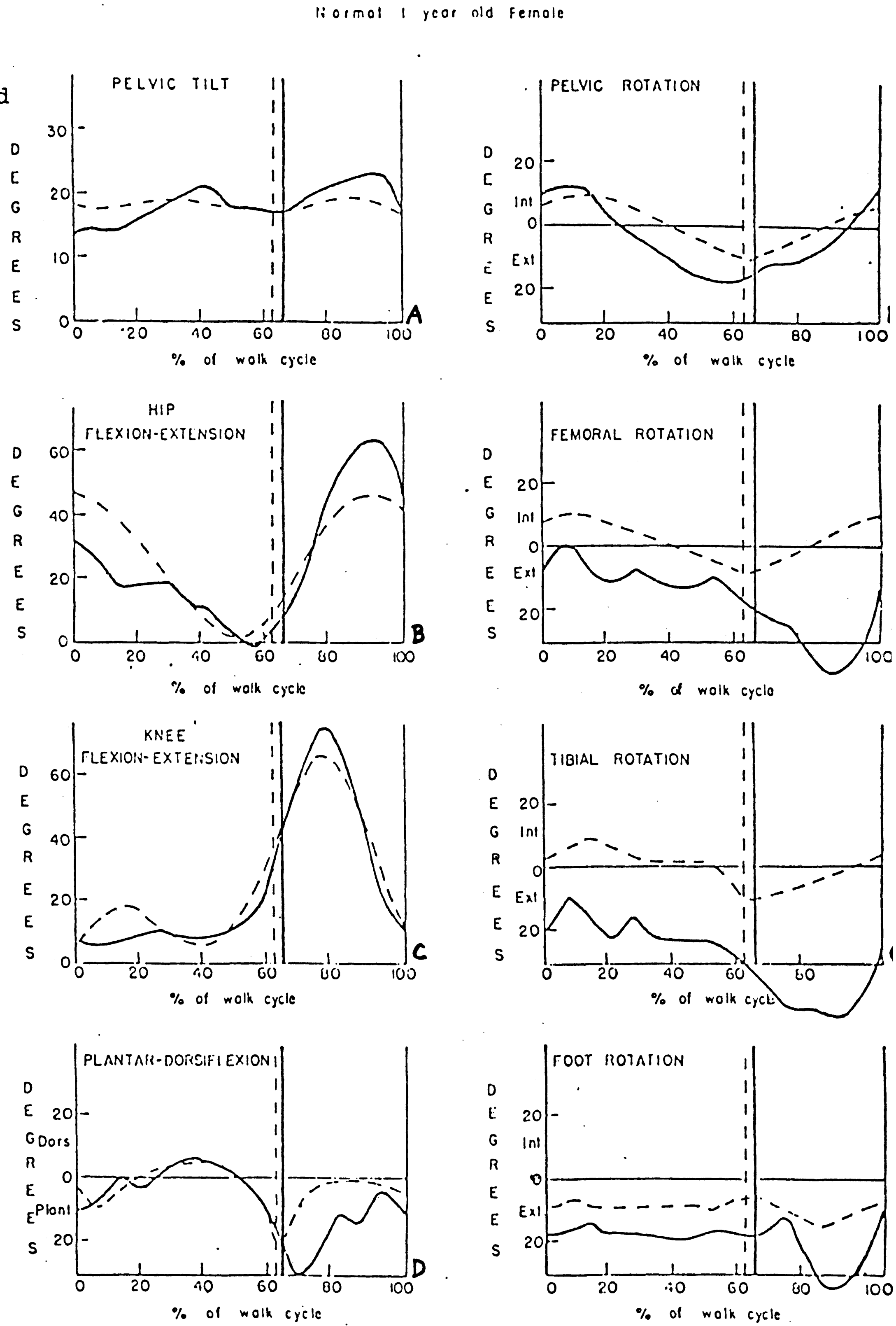
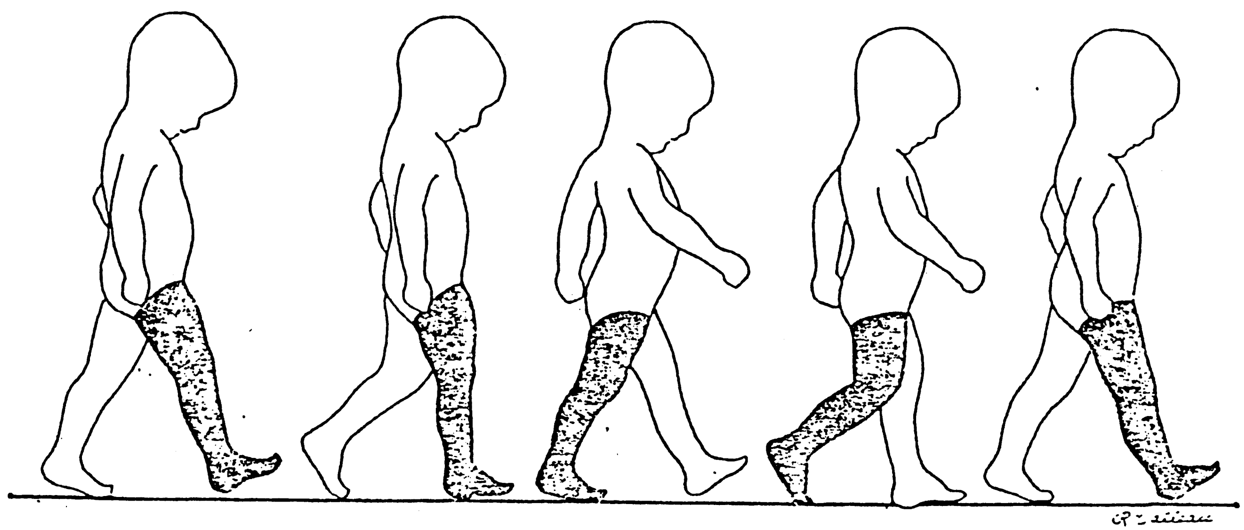


Fig. 5



NORMAL 3 YEAR OLD

Synchronous arm swing, heel strike and apparent trunk stability are indicators of considerable gait maturity in this three year old boy.

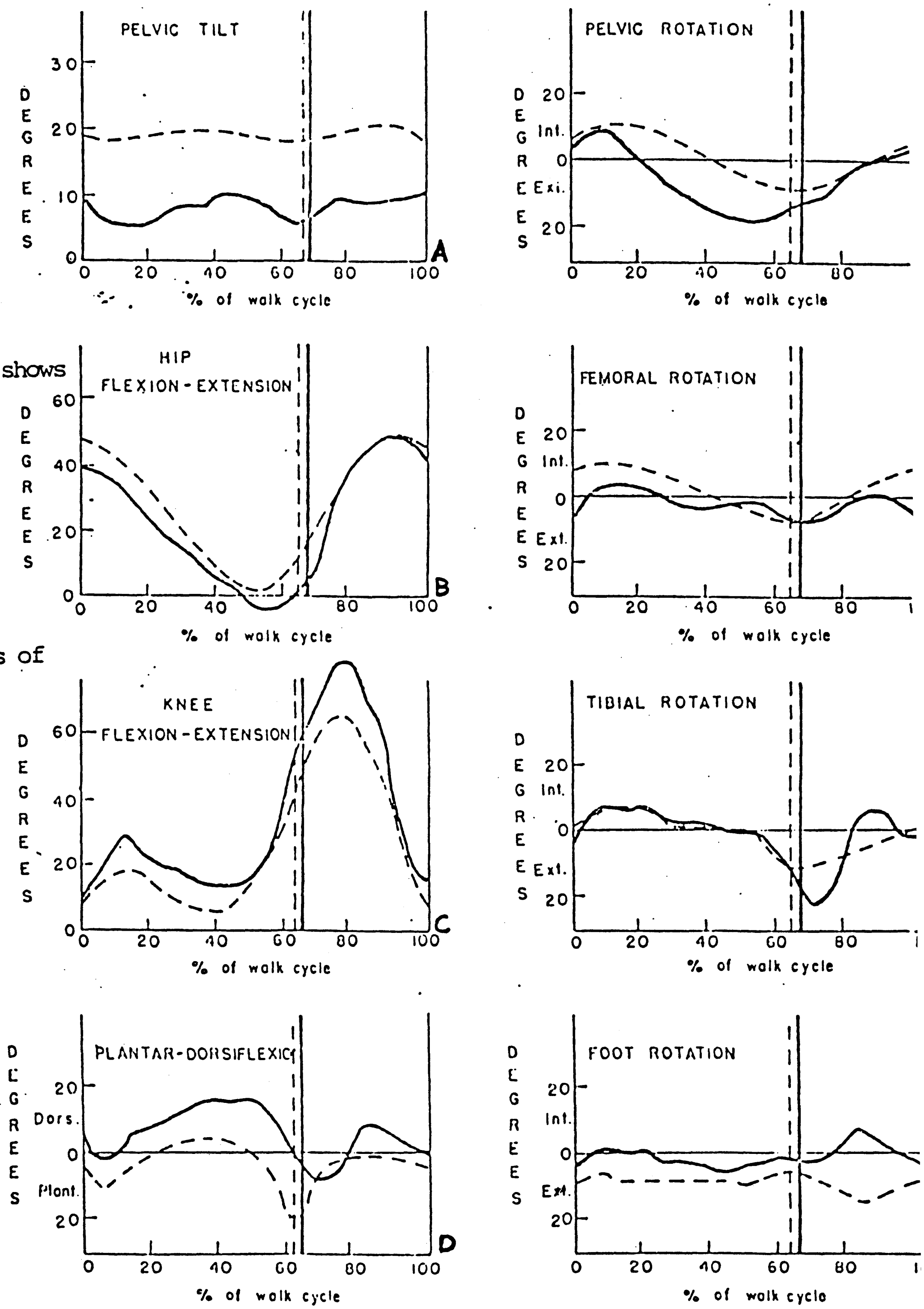
Joint Angular Rotations

Fig. 6

A. to D.
The sagittal plane joint angular rotations of this three year old male are comparable to normal young adult controls.

E. Pelvic rotation shows mild exaggeration of stance phase external rotation.

F to H.
With the exception of some irregularities of foot and tibial rotations in swing phase, femoral tibial foot rotations are similar to young adult controls.



Normal 3 year old Male

While hip and knee angular rotations are very similar to a composite of normal adults (Fig. 6B and 6C), ankle dorsiflexion in stance phase is increased (Fig. 6D). Fully mature gait will be present when better control of ankle musculature brings about the normal plantar flexor activity necessary to facilitate step length. Also Fig. 7.

Case Study A.E.

This six year old normal girl walks with a mature gait pattern (Fig. 8). Walking velocity, step length, and cadence are appropriately related.

General Measurements

	Right	Left
Opp. toe off (% cycle)	10	11
Opp. foot strike (% cycle)	49	52
Single stance (% cycle)	39	40
Toe off (% cycle)	60	63
Step length (cm)	49	49
Stride length (cm)	98	98
Cycle time (sec)	.7	.7
Cadence (steps/min)	171	171
Walking velocity (cm/sec)	140	140
(m/min)	84	84

The increase in pelvic rotation (Fig. 9E) is attributable to rapid free speed cadence. First peak vertical force and mid stance valley (Fig. 9I) are also increased for the same reason. The rapid cadence also is responsible for increases in fore-aft (Fig. 9J) and lateral shear (Fig. 9K). Electromyography reveals normal phasic activity of the vastus medialis, vastus lateralis, gluteus maximus, gastrosoleus, medial and lateral hamstring and anterior compartment muscle groups. Also Fig. 10.

The gait of this child differs in no significant qualitative manner from that of a young adult.

On February 28, 1977, studies of 112 normal children between one and seven years of age had been performed. Data reduction was complete on 92 of these individual studies.

Fourier analysis

THE MODEL

f (t) is some function of gait, such as ankle D/P, at point t of the walking cycle. We fit the model

$$f(t) = \alpha_0 + \sum_{j=1}^{6}\left[{}_j\cos\frac{2\pi}{T}t + \beta_j\sin\frac{2\pi j}{T}t\right]$$

by least squares. In this model α_0 is an overall constant, and T is the total number of observations (equally spaced). Always T is between 16 and 22, usually between 18 and 20.

Force Plate Curves

Fig 7

Normal 3 year old Male

Vertical force, fore-aft shear and medial-lateral shear duplicate adult control values. The curves are terminated at the asterisk because of opposite foot strike on the plate.

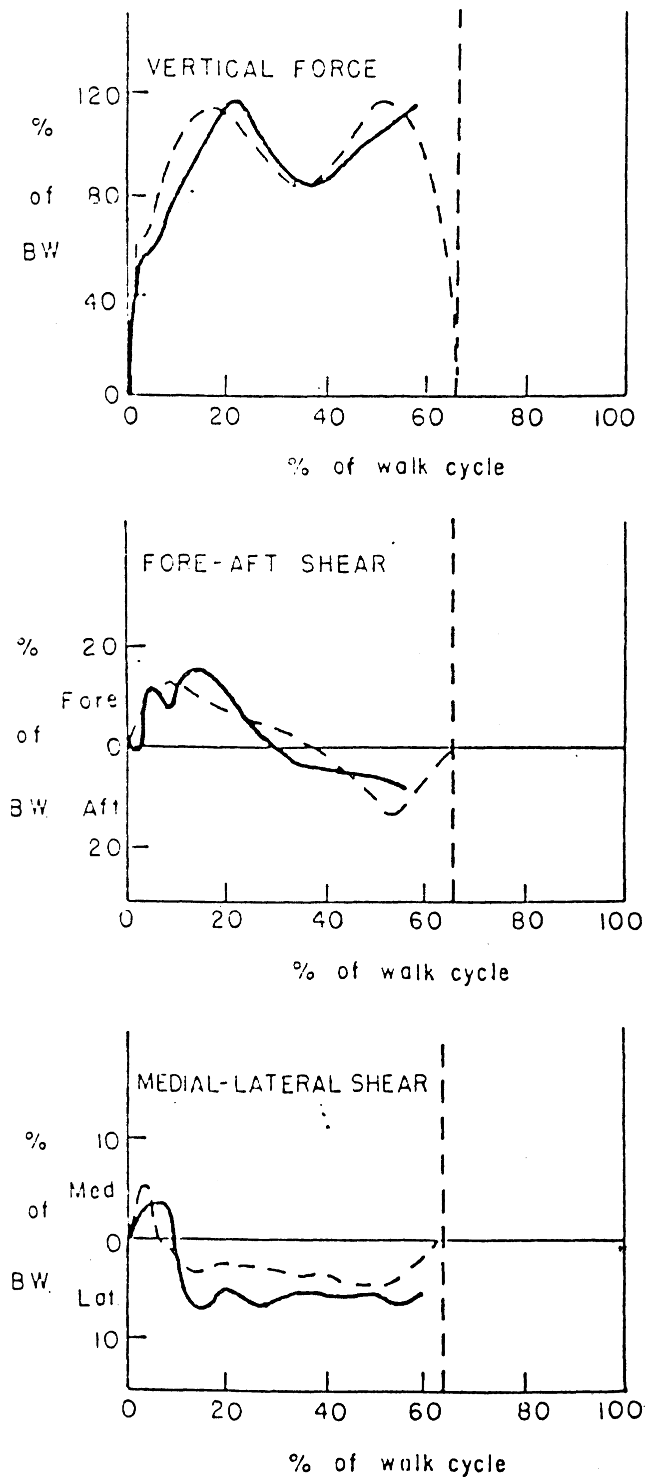
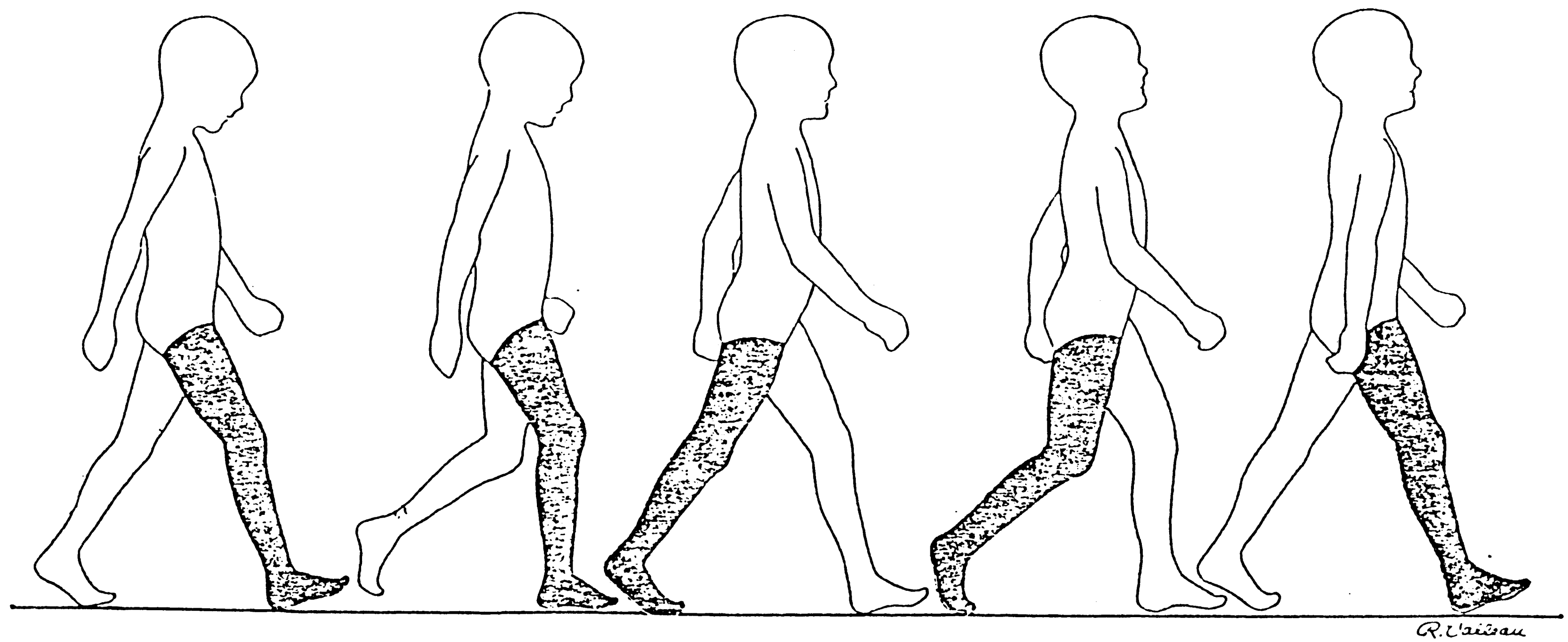


Fig. 8



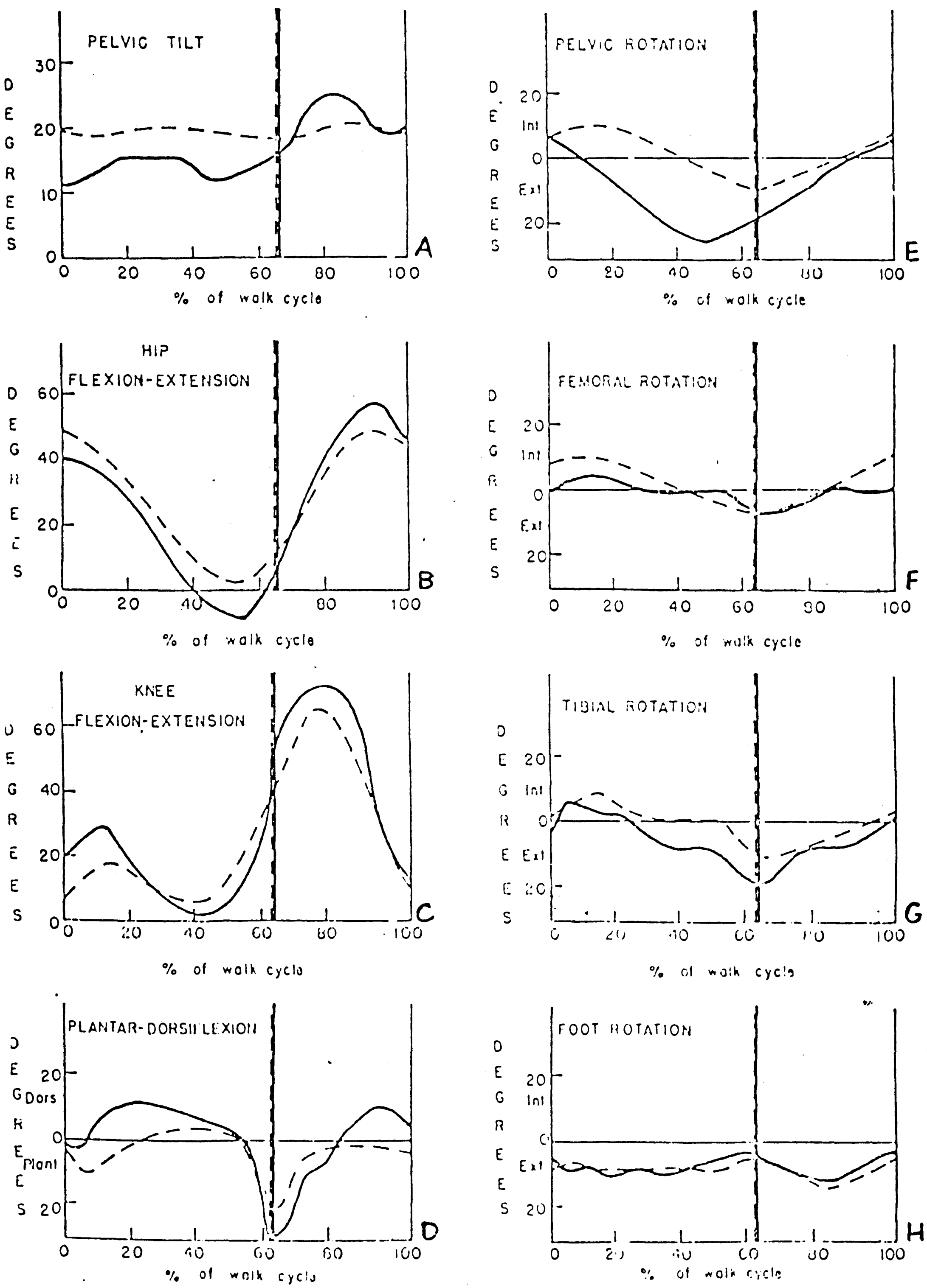
NORMAL 6 YEAR OLD

The gait pattern of this six year old girl resembles very closely that of a young adult.

Joint Angular Rotations

Fig. 9

Normal 6 year old Female



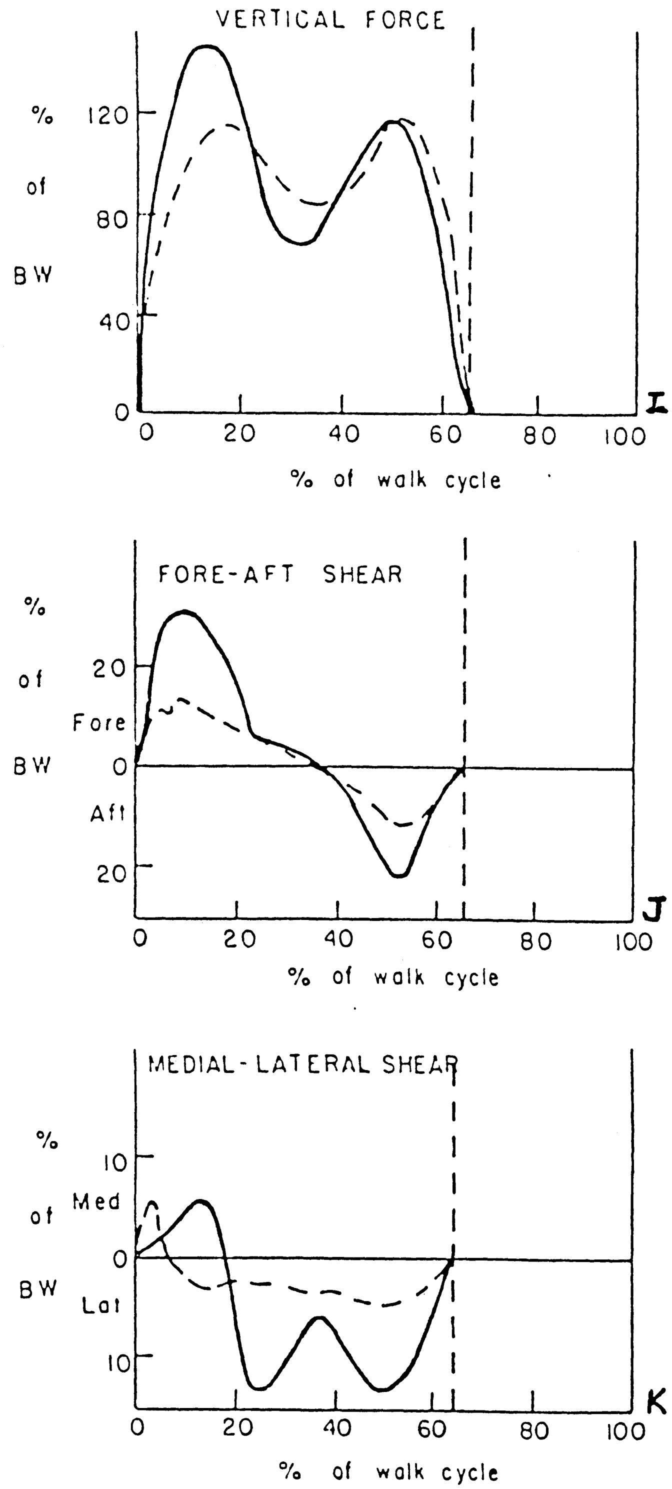
A to D. The sagittal plane joint angular rotations of this six year old girl differ in no significant manner from a composite of curves for young adult controls.

E. Pelvic rotation is increased by high cadence and increased walking velocity.

F to H.
Femoral, tibial and foot rotations are normal.

Force Plate Curves

Fig. 1.0
Normal 6 year old female



I. Vertical force first peak and mid stance valley are increased due to rapid cadence and walking velocity.

J. Fore-aft shear are increased for the same reason.

K. Lateral shear is increased because of rapid cadence and walking velocity.

The ankle plantar flexion/dorsiflexion curves of 32 children demonstrates a complex curve pattern with multiple coefficients significantly different from 0 at the 5 percent level. Somewhat to our surprise 22 of 32 children demonstrated heel strike. (Fig. 11) Slope at zero negative denotes the presence of heel strike, and only 10 of the 32 children demonstrated absent heel strike.

In this relatively small group there was not a significant correlation of heel strike with age. We believe that the explanation for this observation, which appears to be at variance with the findings of previous authors, lies in the 50 frame/second camera rate utilized in our studies. Most of the previous authors utilized a sampling rate which we believe to be too slow to demonstrate a very brief heel strike. It appears from our early data that our initial hypothesis regarding the importance of heel strike as an indicator of the achievement of mature gait is disproved. By contrast with the ankle dorsiflexion/plantar flexion curve, the knee flexion/extension curve reveals a much smaller number of relatively important coefficients and a higher explanatory power of the largest coefficient. (Fig. 12). The knee curve also appeared to have less variation in the children than the ankle plantar flexion/dorsiflexion curve. From our preliminary results it appears likely that the angular rotations in the sagittal plane in very small children differ only slightly from adult curve patterns. It appears that the development of adequate step length and walking velocity may correlate much more closely with overall gait maturity than angular rotations at individual joints.

The surprising similarity of angular rotations between very small children and adults has led us to critically examine other measurements such as step length and the factors influencing it. Walking velocity, age and pelvic rotation are significant variables affecting step length, however, pelvic rotation has a negative correlation with step length. An equation including these variables can be constructed which explains 90 percent of the variability in step length.

$$\text{Step Length} = 5.3203 + (2.9446)\,(\text{Age}) + (.1561)\,(\text{Walking Velocity}) + (.1788)\,(\text{Pelvic Rotation})$$

It is well known that the step factor, which is defined as the step length divided by leg length, increases from age one to four years. Scrutton (12) describes a mean step length at one year of 10 inches, at two years of 11.5 inches, at three years of 13 inches, 4 years at 15 inches. Various explanations have been given for this very rapid increase in step length. Improvement in balance during single limb support is one possible explanation. Improvement in strength and control at the ankle relating to the cephalocaudal progression of myelinization is a second explanation. A third explanation is that pelvic rotation increases with age and promotes greater step length. From our preliminary studies we believe this explanation to be incorrect.

The second major new area of investigation is the determination of sagittal plane torque in the lower extremity joints. Normalized comparative torques in the two to three year age range when compared with the 4 to 7 year old children appears to show a predominance of hip flexion torque with limited hip extension torque. The numbers are small and many more studies will be drawn. We also found in the ankle torque determinations a trend toward

Fig. 11

ANKLE D/P
(32 Children)

Cell #	Age	# Coefficients Significantly Different from 0 at 5% Level	(averages)	Relatively Important Coefficients**	Slope at 0 - implies heel strike***	*
1748	1	8	(averages)	B_1,B_2,B_3	- 9.28	22
4724	1	3	5.5	B_1	-12.42	65
4340	1-1/2	2	2	a_2	- 1.77	60
1652	2	0	2.5		- 1.14	24
1996	2	5		B_1,B_2	- .55	43
2708	2-1/2	7		B_1,B_2	- 2.89	34
5012	2-1/2	3	4.25	B_1	+ 4.68	57
3284	2-1/2	3		B_1,B_2	-10.53	50
1940	2-1/2	4		B_1	- .35	48
4532	3	6		a_1,a_2,B_1,B_2	+ 1.89	26
3476	3	5	5	B_2	+ 4.34	49
3572	3	2		B_1,B_2	- 4.49	51
2324	3	8		a_2	- .97	36
4820	3	5		B_1,B_2	- 7.40	54
4244	3	4		B_2	+ 1.41	41
4916	4	3	3.67	a_2,B_2	- 3.47	35
1844	4	5		B_1	+ 1.29	33
3188	4	3		B_2	+ 2.72	53
2132	5	1		B_2	-11.62	65
3860	5	4	3.17	a_2,B_2	+ 1.06	39
5108	5	4		a_2,B_1,B_2	- 1.06	39
2900	5	2		B_2	+ 1.84	56
4148	5	2		B_1,B_2	- 3.75	46
4628	5	6		B_1	+ 2.57	49
4436	6	5		B_2,B_3	- 1.90	43
4052	6	6	4.75	a_1,a_2,a_3,B_1,B_2	- 3.90	21
2516	6	4		B_1,B_2	+ 2.50	46
1556	6	4		B_1,B_2	- 6.09	41
2612	7	9		B_1	- 5.72	52
2804	7	6	5	B_1,B_2	- .19	37
3956	7	4		B_1,B_2	- .73	50
1460	7	1		B_2	- .35	65

*Explanatory power of largest coefficient (in%)

**B_1 was significant 20 times; B_2 was significant 23 times

***Heel strike for 22 children
None for 10 children

Sutherland cont.

Fig. 12 KNEE F/E (Rt.)

Cell #	Age	# Coefficients Significantly Different from 0 at 5% level	Relatively Important Coefficients	Explanatory Power of Largest Coefficient (%)
1748	1	7	B_1	64
4724	1	4	B_1	63
4340	1-1/2	5	B_1	67
1652	2	3	B_1	59
2996	2	3	B_1	50
2708	2-1/2	6	B_1	57
5012	2-1/2	5	a_2, B_1	45
3284	2-1/2	6	B_1	66
1940	2-1/2	5	a_2	56
4532	3	3	B_1	62
3476	3	5	B_1	69
3572	3	5	B_1	60
2324	3	3	a_2	58
4820	3	5	a_2, B_1	53
4244	3	9	a_2, B_1	43
4916	4	5	a_2, B_1	51
1844	4	5	B_1	60
3188	4	4	B_1	57
2132	5	5	B_1	62
3860	5	3	a_2, B_1	50
5108	5	3	a_2, B_1	56
2900	5	8	B_1	59
4148	5	6	B_1	57
4628	5	4	B_1	63
4436	6	5	B_1	62
4052	6	5	B_1	66
2516	6	4	a_2, B_1	52
1556	6	7	B_1	58
2612	7	5	a_2, B_1	54
2804	7	4	B_1	74
3956	7	7	B_1	66
1460	7	5	a_2, B_1	41

Sutherland

Fig. 13

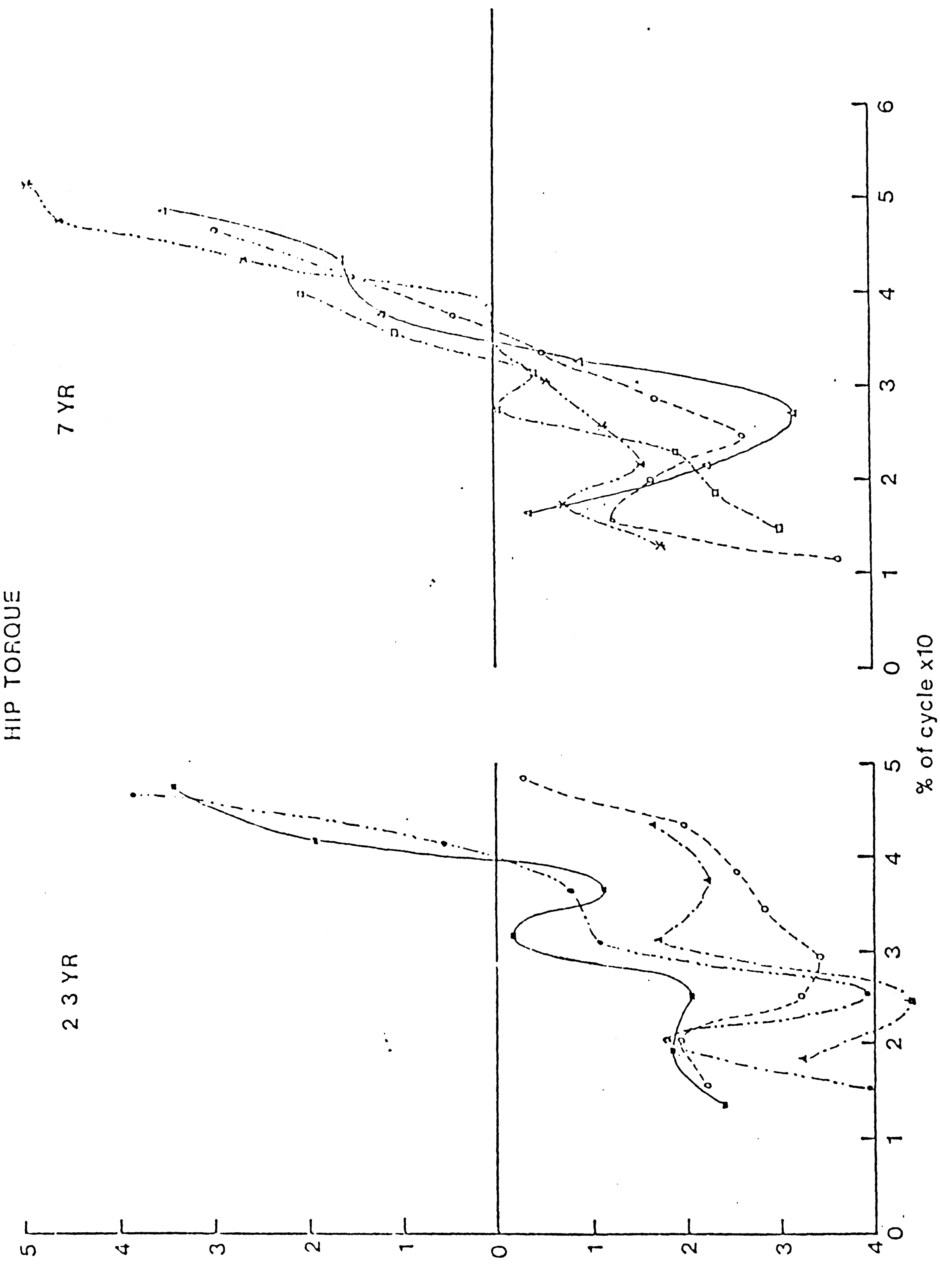
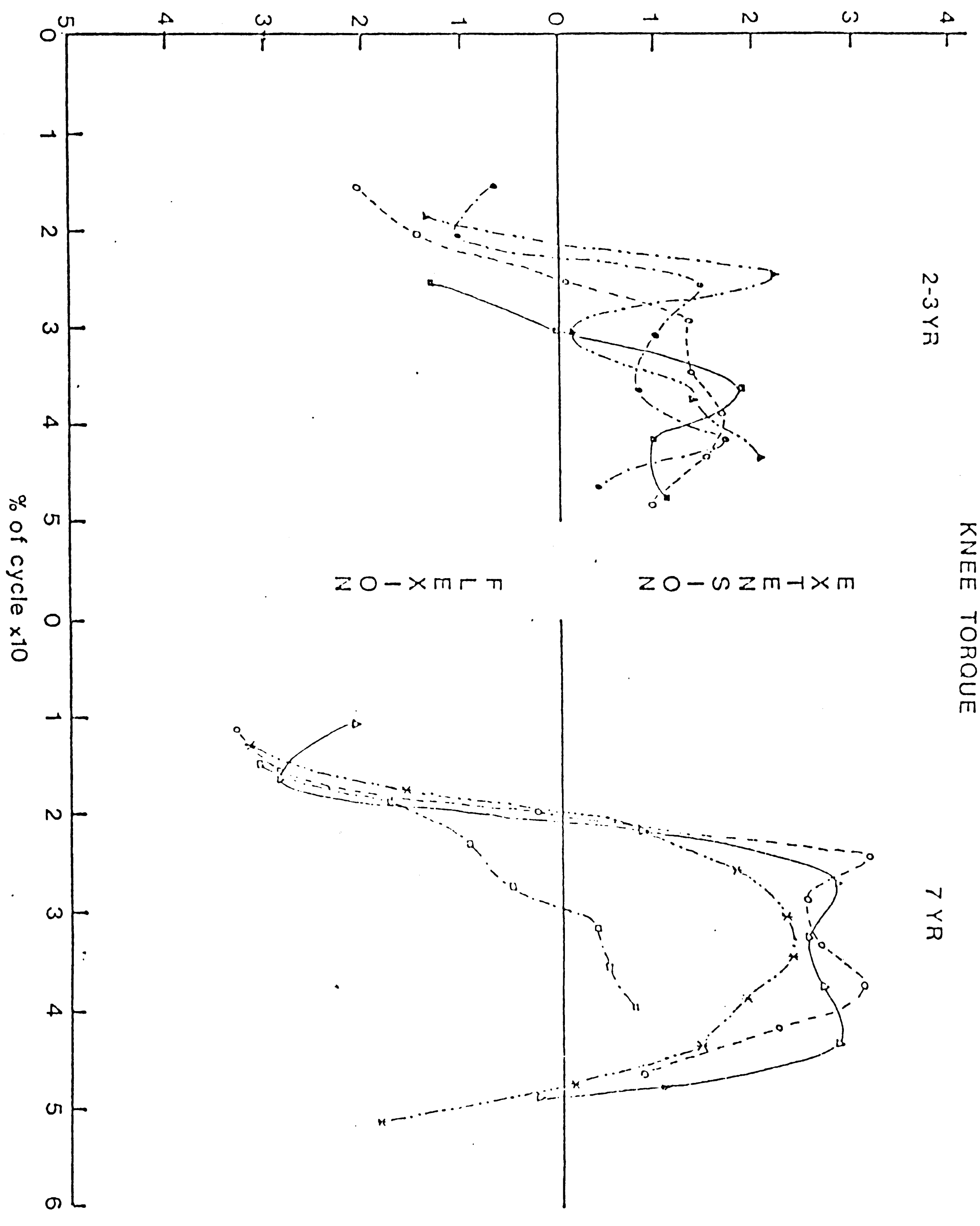


Fig. 14

KNEE TORQUE



greater variation in the younger age group. This would appear to correlate with the restricted step length, and it may be explained by the cephalo-caudal myelinization sequence (10 and 15).

Initial results of electromyography suggest a definite trend toward stance phase prolongation of the gluteus maximus and hamstring muscles. A predominance of hip flexion torque would necessitate compensatory hip extensor muscle firing. Again, this is a preliminary observation and will require greater numbers for statistical significance. Also see Figs. 13, 14 and 15.

CALCANEAL LIMP

Case Study - F.F.

This thirteen year old male had polio at age one year with primary residual paralysis of the left gastrocnemius and soleus muscles (grade 0) (Fig. 16).

tibialis posterior 4
flexor hallucis longus 4
flexor digitorium longus 4
extensor digitorium longus 4
peroneus longus 5
peroneus brevis 5

In spite of extreme plantar flexor weakness, he is a community ambulator and is brace free. His "calcaneal limp" is quite obvious and progressive calcaneal deformity has been documented.

General Measurements

	Right	Left
Single stance phase (% cycle)	38	36
Step length (cm)	40	61
Cadence (steps/min)	126	
Walking velocity (cm/sec)	106	

Primary Abnormality

The primary movement abnormality is apparent in the graph of left ankle plantar flexion/dorsiflexion (Fig. 17H). Because muscle strength is lacking to decelerate forward rotation of the tibia on the talus (15, 17), ankle dorsiflexion increases to 40 degrees. No ankle plantar flexion occurs until after toe off. Opposite step length as compared with ipsilateral limb is reduced 35%. Reduction in opposite step length, increased double support time and reduced walking velocity are common in this disorder.

Compensatory Mechanisms

Since poliomyelitis leaves the control system intact, compensatory mechanisms are at work to smooth the gait and minimize energy consumption. In the ipsilateral limb, electromyography revealed premature phasic activity in the tibialis posterior, peroneus longus and peroneus brevis. In the contralateral limb, first peak of the vertical force curve is exaggerated (Fig. 18I). Fore and aft shear are also increased (Fig. 18J).

Sutherland cont.

Surgical treatment has subsequently been carried out to correct the calcaneus deformity and to improve the limp. A Beak triple arthrodesis (14) with a generous subtalar wedge was performed to increase the calcaneal lever arm (Fig. 19B). This was followed in several months by transfer of the peroneus longus and tibialis anterior to the os calcis. Followup studies are not yet available.

GLUTEUS MAXIMUS AND QUADRICEPS WEAKNESS

Case Study - M.J.

This eight year old male has Duchenne muscular dystrophy (Figs. 20, 21). At the time of this study he walks with moderate difficulty, and without effective intervention his walking ability can be expected to end in two years or less. Mild abduction contractures are noted of both hips and 10 degree ankle equinus contractures are present. The muscle ratings are:

gluteus maximus, right 2, left 2
quadriceps, right 2+, left 2
gastrosoleus, right 4+, left 4+

General Measurements

	Right	Left
Opposite toe off (% of cycle)	15	15
Opposite foot strike (% of cycle)	50	50
Single stance (% of cycle)	35	35
Step length (cm)	37	39
Cycle time (per sec)	1.3	1.3
Cadence (steps/min)	92	
Walking velocity (cm/sec)	58	

Primary Abnormality

While there is generalized muscle weakness the proximal muscles of the extremities and the trunk muscles show the earliest and greatest involvement. Weakness of the gluteus maximus and quadriceps muscles are responsible in large part for the gait abnormalities.

Compensatory Changes

In the sagittal plane the most striking abnormality is a peculiar lordosis accompanied by posterior alignment of the arms behind the trunk. Weakness of the gluteus maximus necessitates maintenance of the saggittal plane force vector $\overline{R}$ through or near the hip joint center (Fig. 21). This is accomplished by arching of the back and posterior arm positioning. Weakness of the quadriceps muscle is compensated for by movement of the force vector line in front of the knee joint producing knee extension (Fig. 21). This is accomplished by overactivity of the ankle plantar flexors and by prolonged phasic stance phase activity of the quadriceps muscle. Evidence for these compensatory changes is seen in: 1) the graph of ankle plantar flexion/dorsiflexion showing plantar flexion at foot strike (Fig. 21D), 2) in the graph of knee flexion/extension showing extended knee position throughout stance (Fig. 21C), 3) in the center of pressure diagram showing concentration of pressure in the metatarsal head region (Fig. 22L). As long as the center of rotation of the hip, knee and ankle can be held close to the force vector line, he will continue ambulation. When contractures prevent satisfactory alignment, walking will become impractical. Extension of ambulation for three to four years can usually be achieved by contracture release, lower extremity long leg braces and by a vigorous physical therapy program.

While satisfactory compensatory mechanisms were apparent when this study was performed, walking became more labored and contractures of the hips were noted three months later. The patient is now awaiting surgical release of contractures and immediate reambulation in casts and braces. In addition to the prevention of scoliosis, continued ambulation provides profound functional and psychological benefits for the patient. Also see Figs. 23-27.

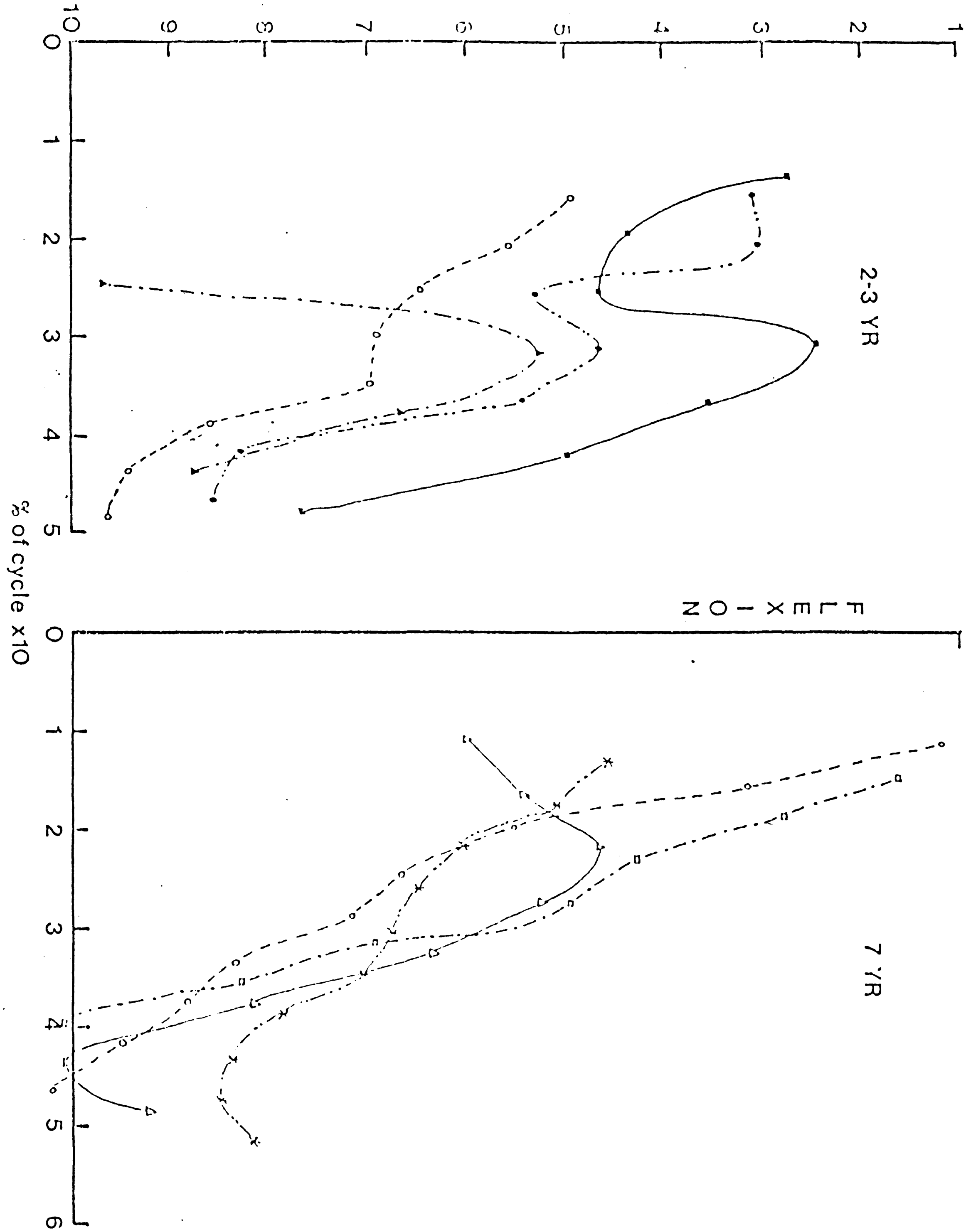
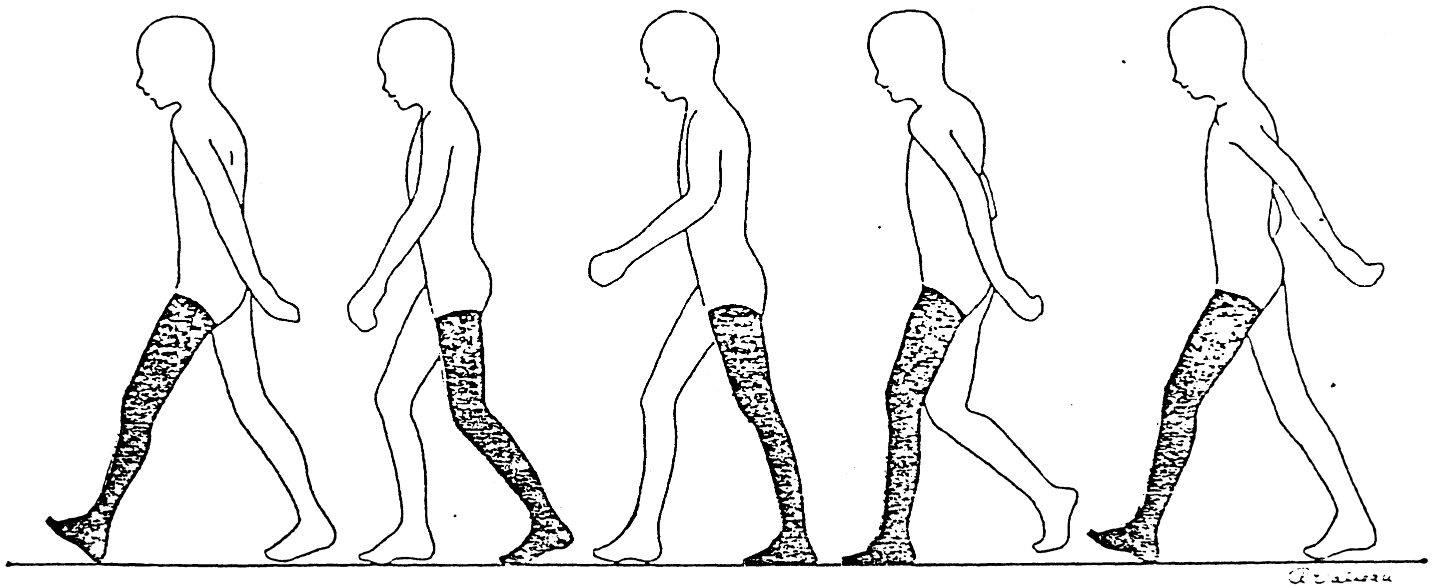


Fig. 15 ANKLE TORQUE

Fig. 16

Poliomyclitis



CALCANEAL LIMP

Poliomyelitis at age one year caused permanent paralysis of the left gastrocnemius and soleus muscles. Note increased ankle dorsiflexion in stance phase. Opposite step length is reduced.

Sutherland

CALCANEAL LIMP

Fig. 17

Poliomyelitis

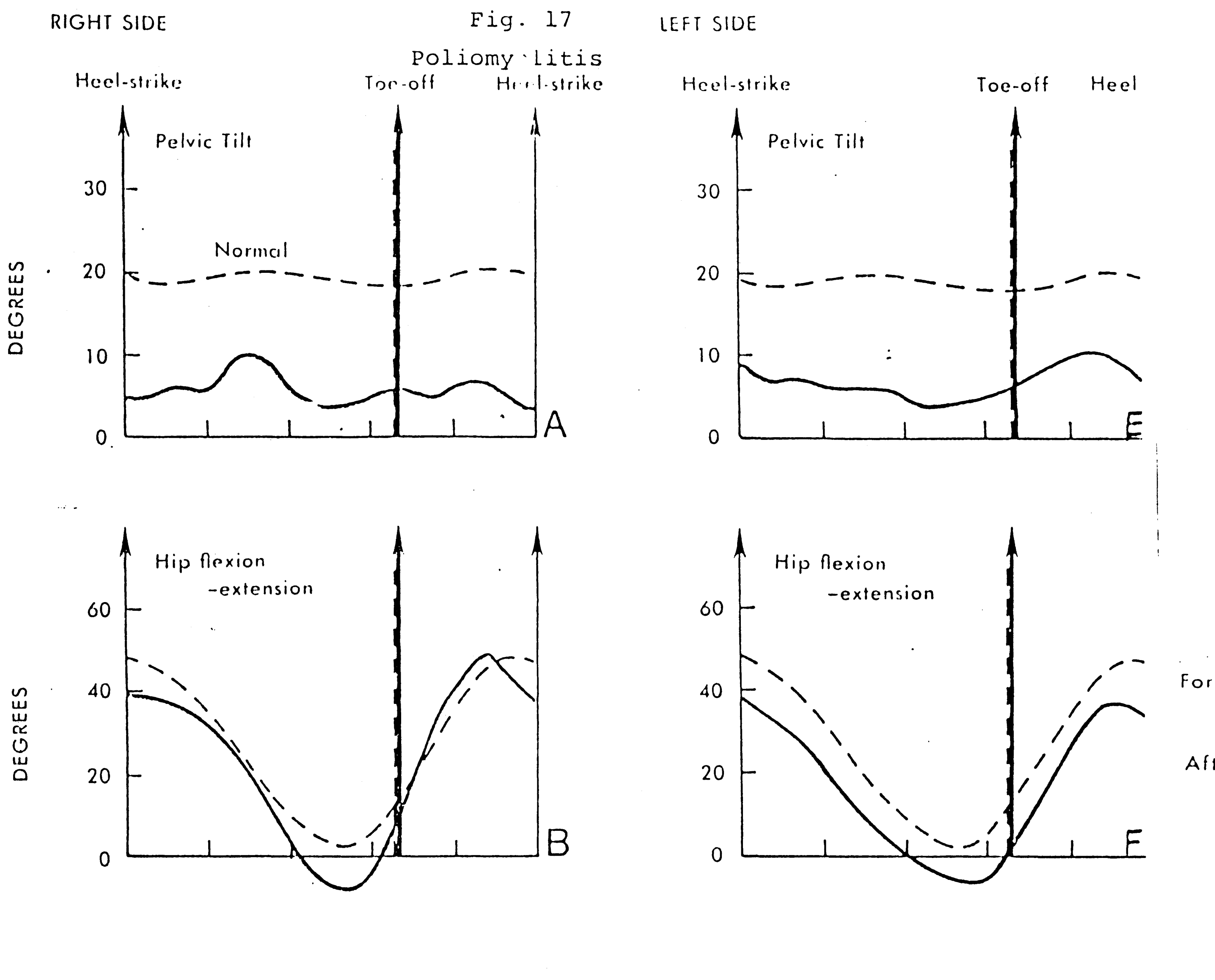
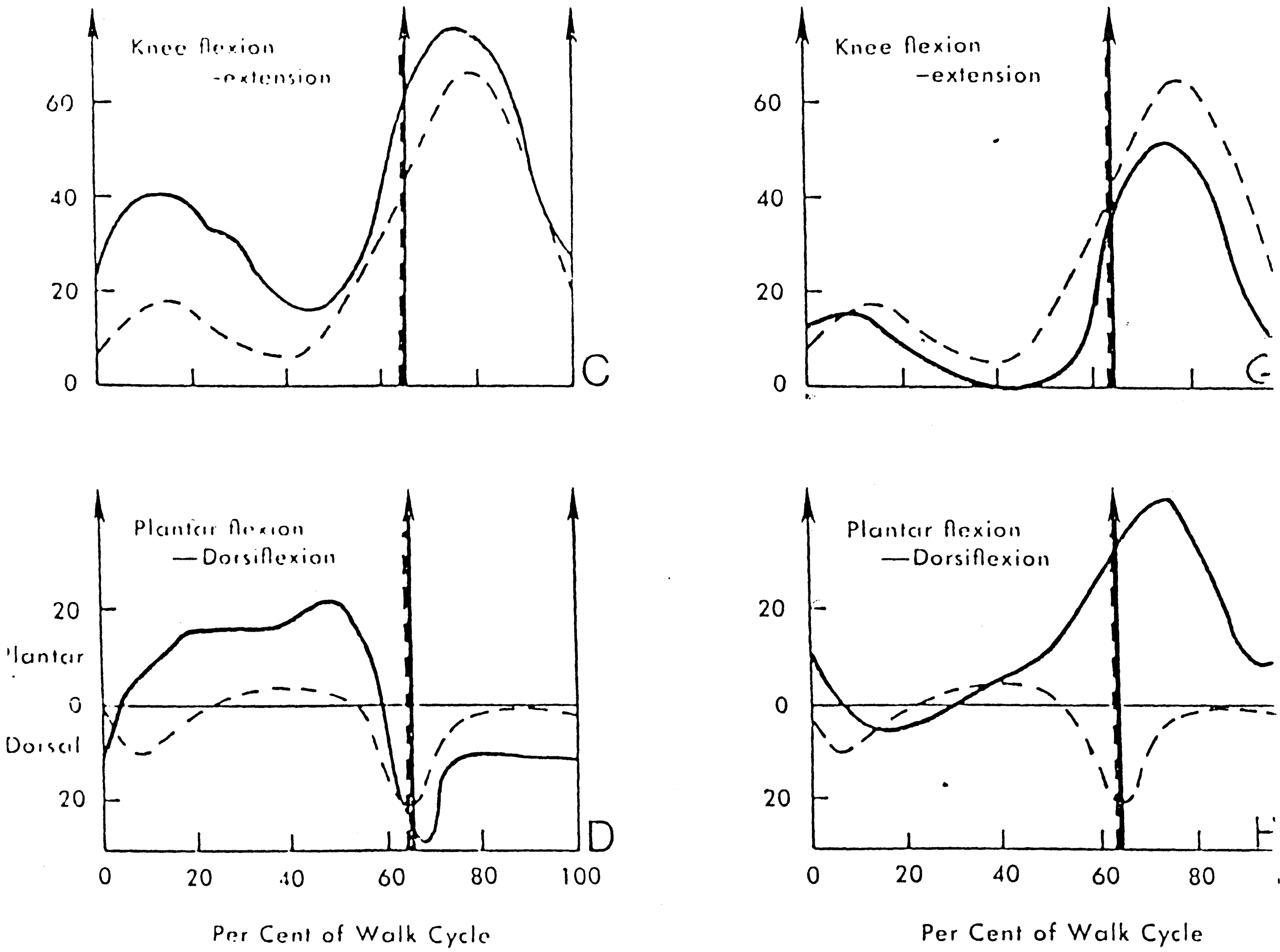


Fig. 17 cont.



A to D. Increased knee and ankle flexion in stance phase in the contralateral limb may be compensatory or due to mild polio paresis of the right leg. No functional problems relating to this limb were noted.

E to H. The primary movement abnormality is excessive stance phase ankle dorsiflexion. Note the absence of reversal until after toe off H.

Fig. 18

Force Pla:e Curves

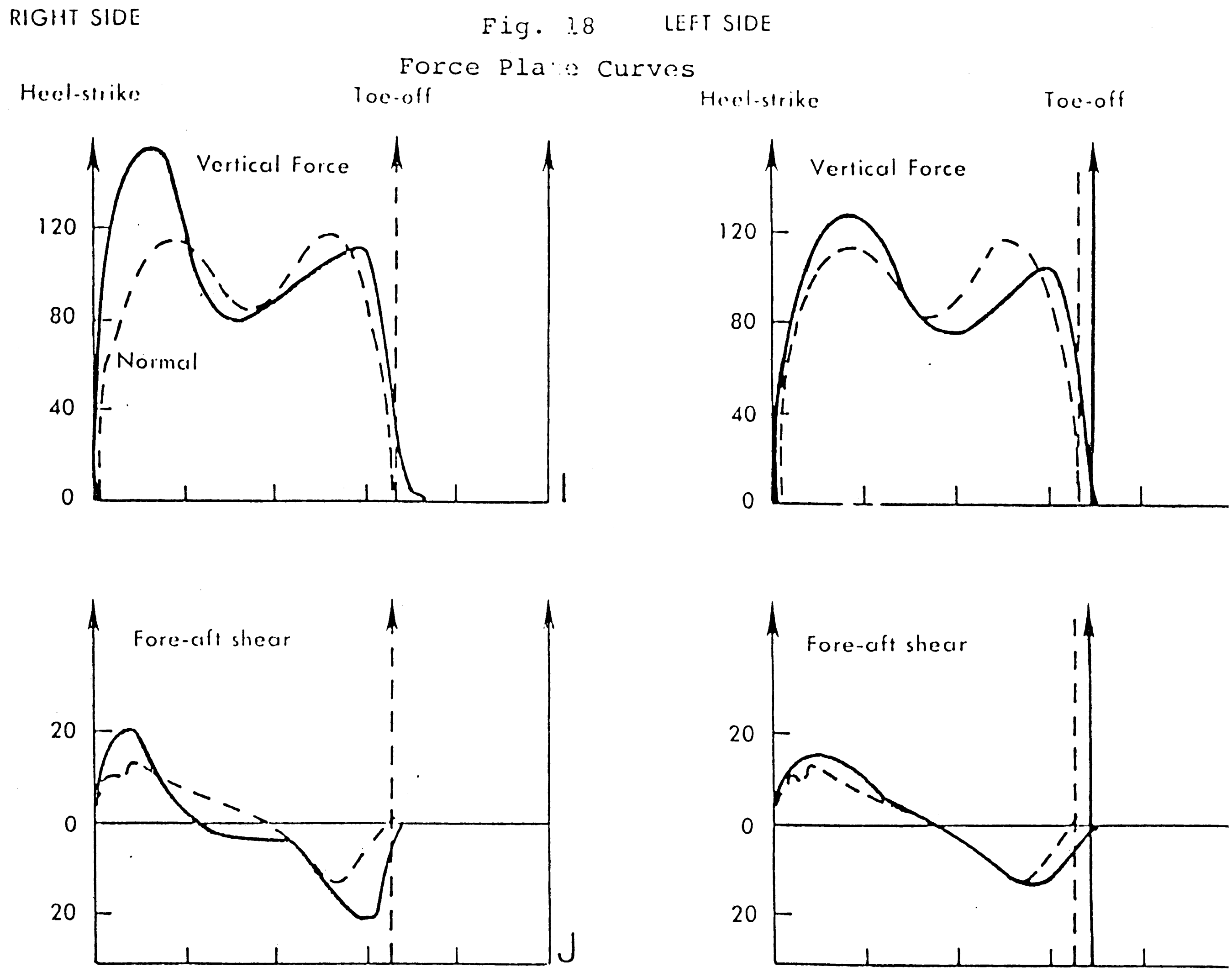
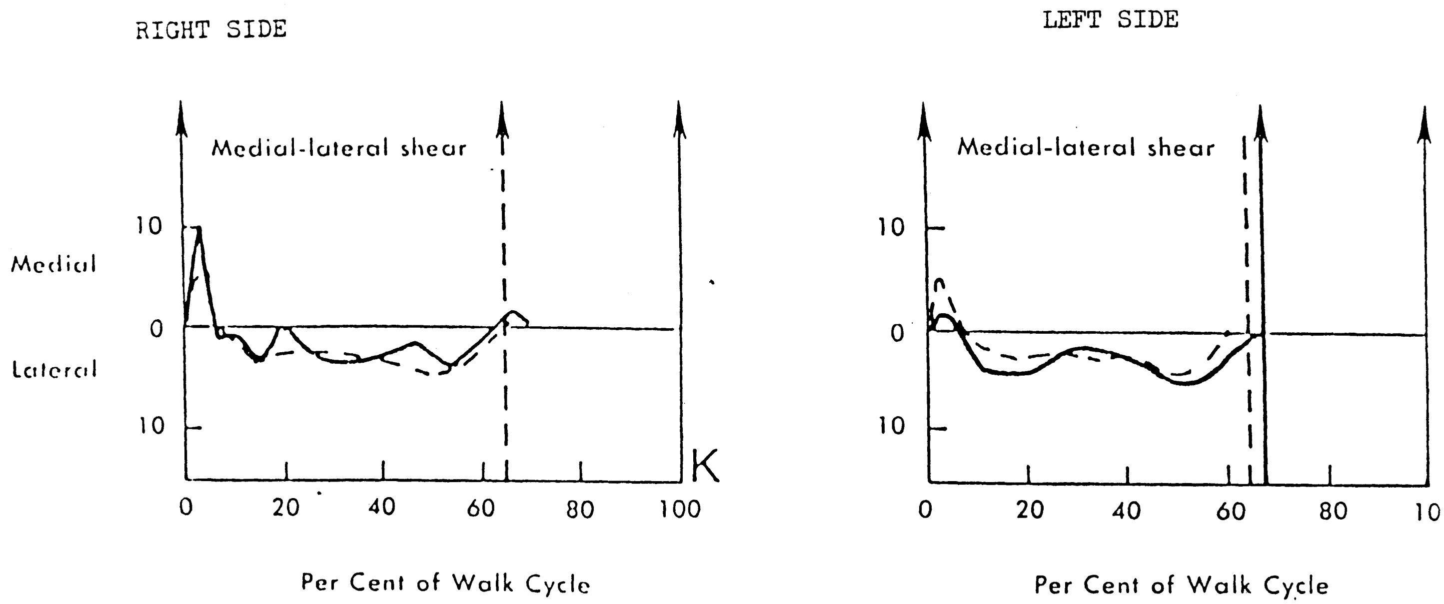


Fig. 18 cont.



I. On the contralateral side there is compensatory increase in first peak vertical force.

J. There is also compensatory increase of fore-aft shear.

K. There is some increase in medial-lateral shear.

L. On the side of gastrocnemius and soleus paralysis second peak vertical force is diminished. Such a reduction occurs regularly with experimental tibial nerve block to simulate calcaneus gait. (18)

M to N. Fore-aft shear and medial-lateral shear are normal.

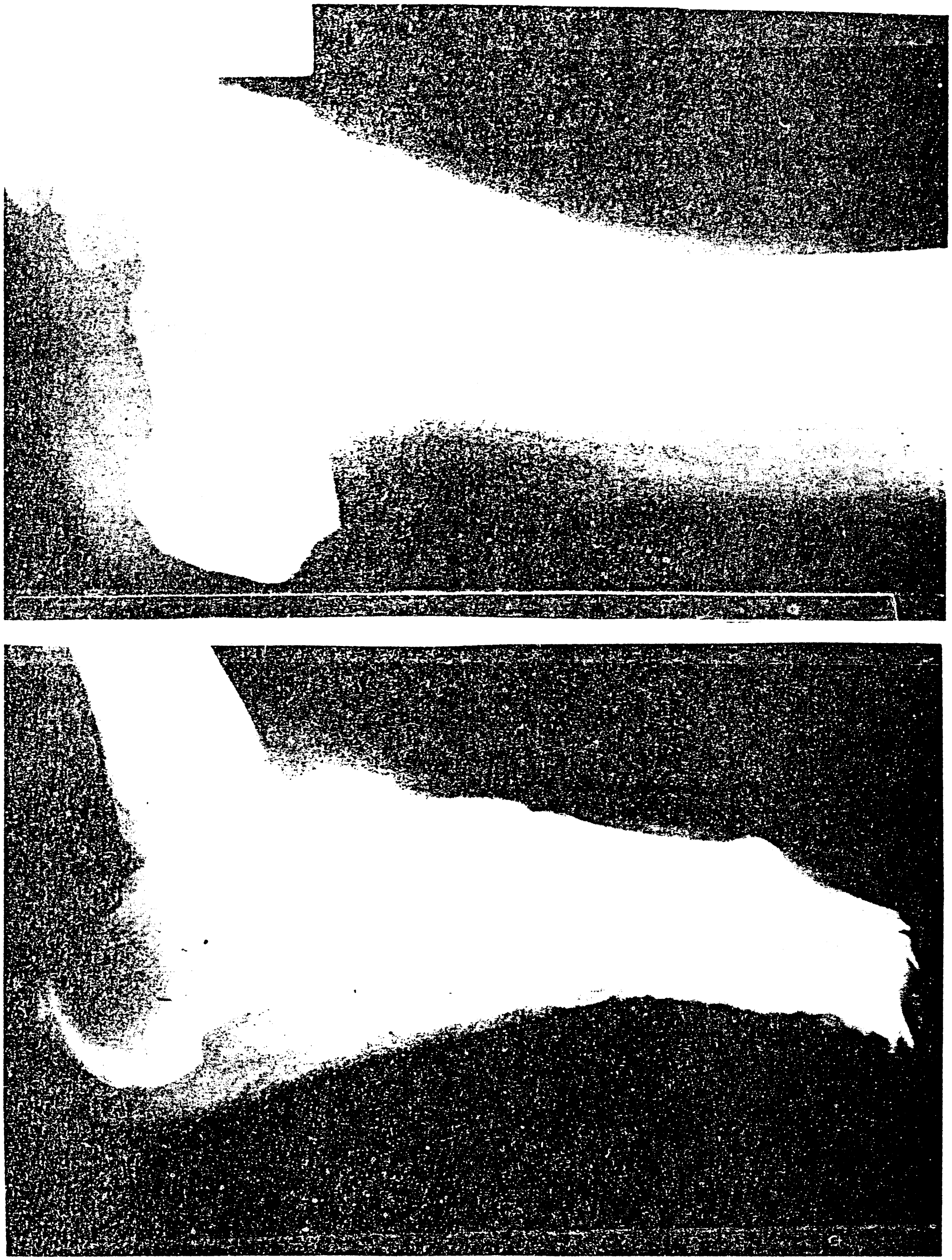


Figure 19. Poliomyelitis - Calcaneal Deformity (title)

Legend

Preoperative A and Postoperative B lateral roentgenograms of the foot seven months following triple arthrodesis for calcaneal deformity and limp. Transfers of the tendons of the peroneus longus and tibialis anterior to the os calcis were the last stage of the surgical treatment plan.

Figure 20. Duchenne Muscular Dystrophy (title)

Legend

The dynamic posture in single support of an eight year old male with Duchenne dystrophy is contrasted with a seven year old normal male. Note the arched back and posterior arm position in the patient with dystrophy. The line of application of the floor reaction force $\bar{R}$ remains close to the hip joint center and in front of the knee joint center in the patient with dystrophy. Quadriceps and gluteus maximus weakness together produce the characteristic gait.

Fig. 20

Duchenne Muscular Dystrophy

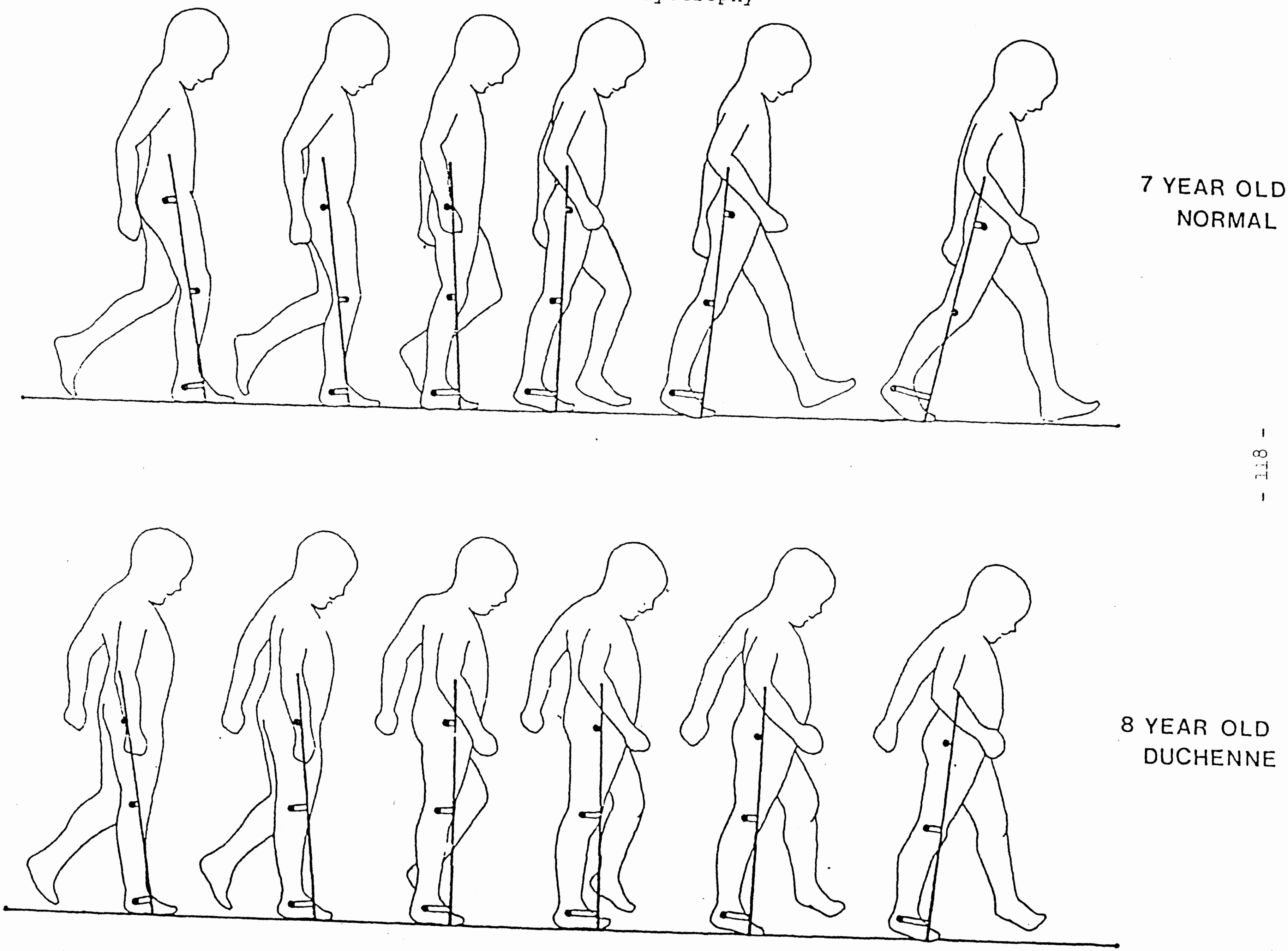


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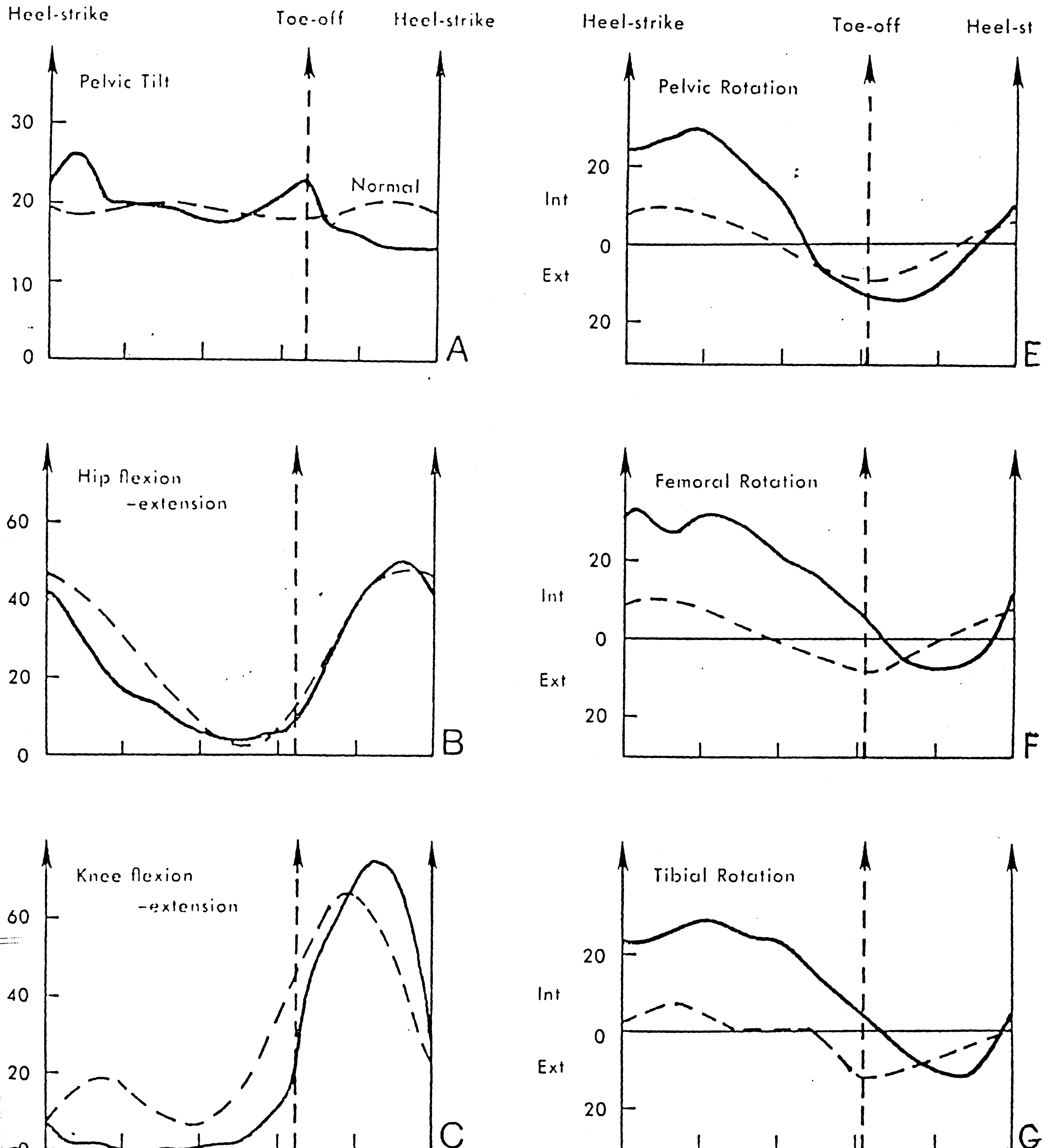
Fig. 21

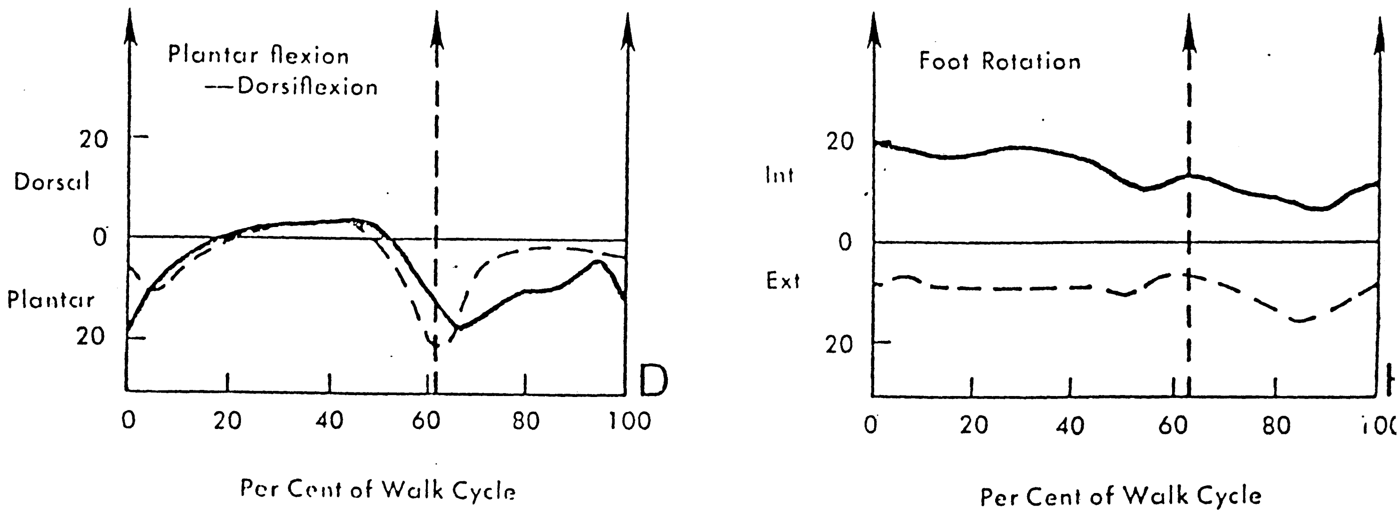
Duchenne Muscular Dystrophy - Joint Angular Rotations

LEFT SIDE



Sutherland

Fig. 21 cont.



Sagittal and transverse plane joint angular rotations of eight year old male with Duchenne dystrophy.

A. While excessive anterior pelvic tilt is common in later ambulatory stage of this disease, this has not yet occurred.

C. Full knee extension is present throught stance.

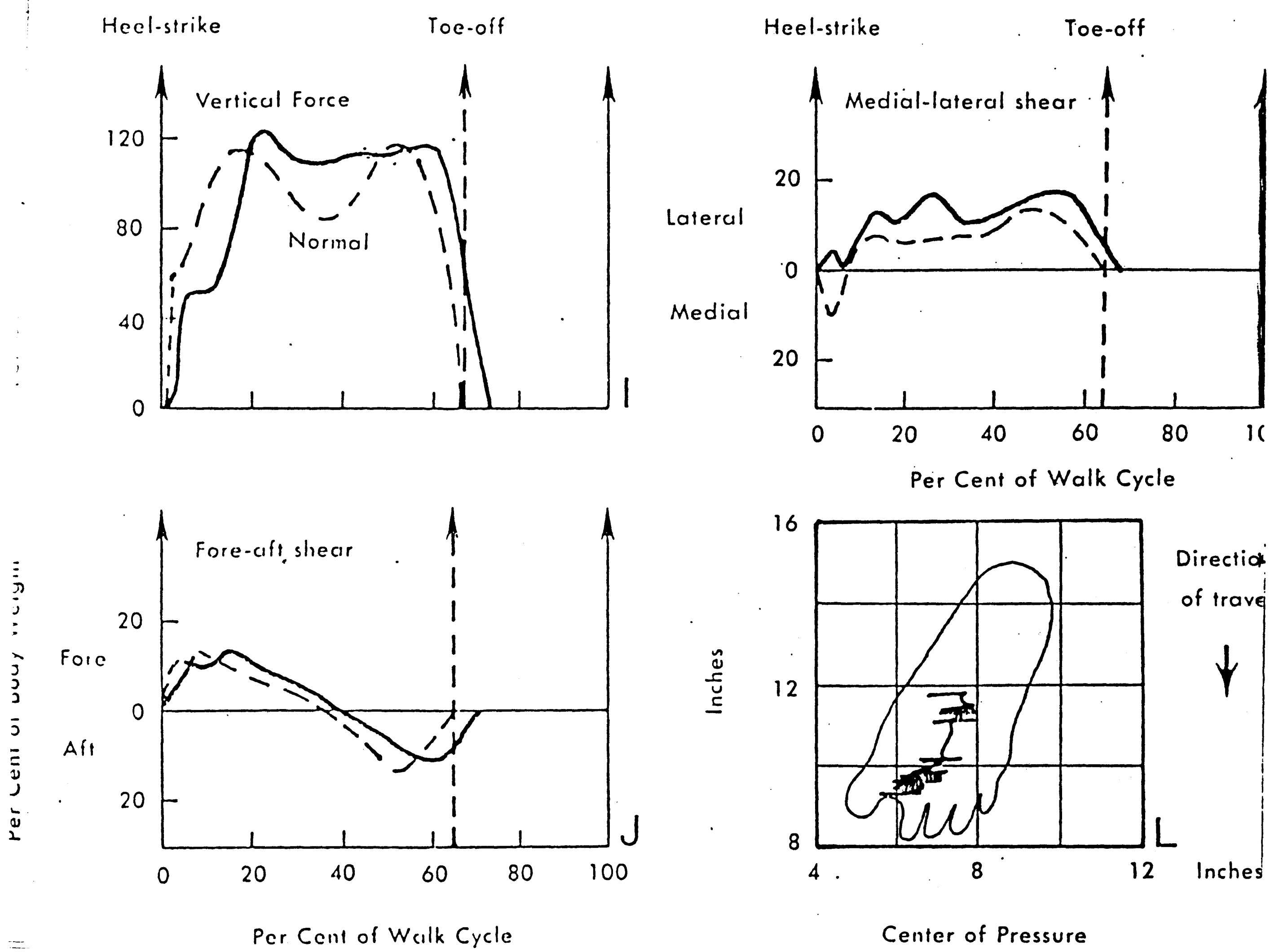
D. Note increased plantar flexion at heel strike and drop foot in swing.

E to H. Stance phase internal rotations of pelvis, femur, tibia and foot are increased.

Fig. 22

Duchenne Muscular Dystrophy - Force Plate Curves

LEFT SIDE



I. Vertical force mid stance valley is absent.

J. Fore-aft shear is normal.

K. Medial shear is missing.

L. Center of pressure concentration is in the forefoot due to equinus contracture and to compensatory overactivity of the plantar flexors.

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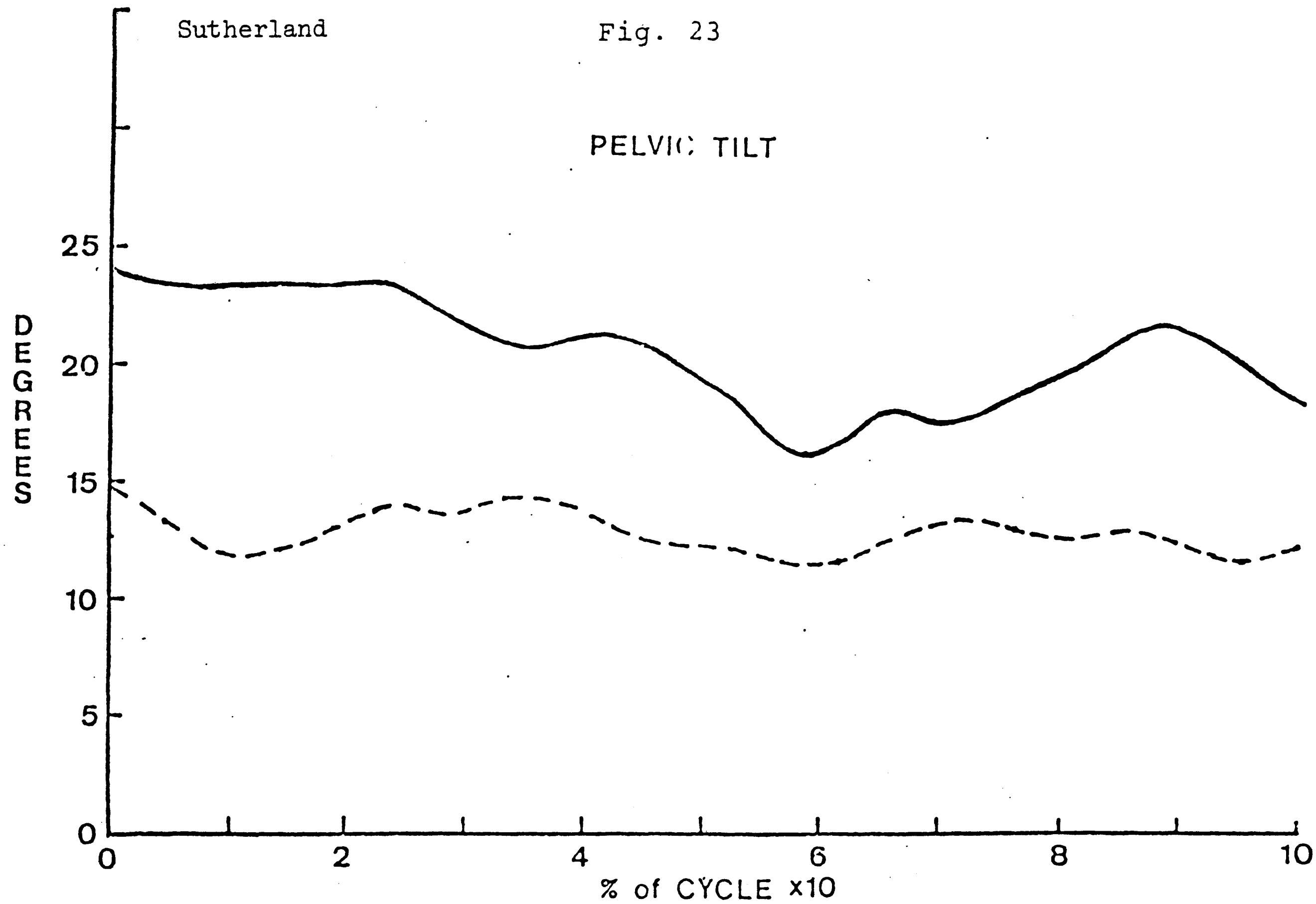
Fig. 23



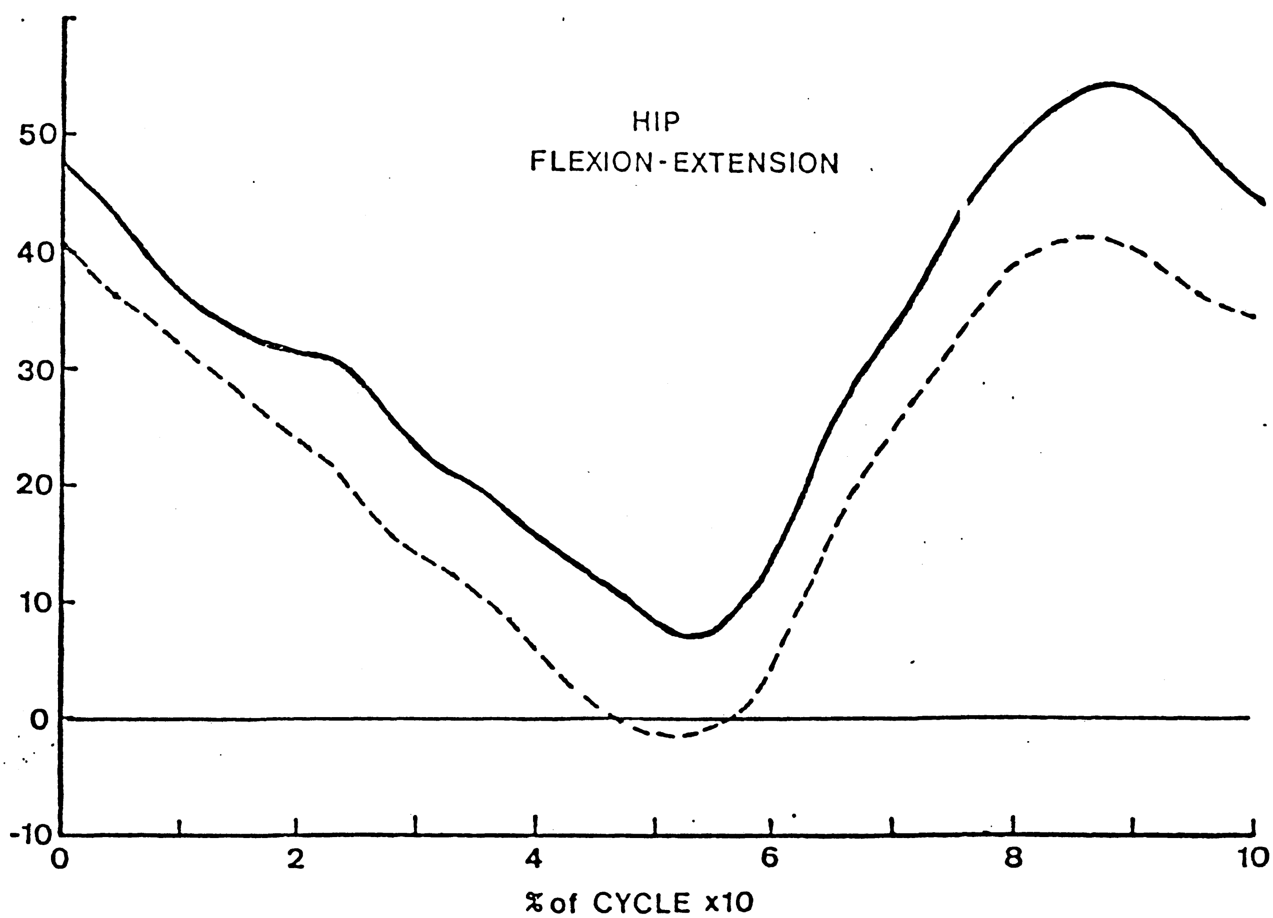


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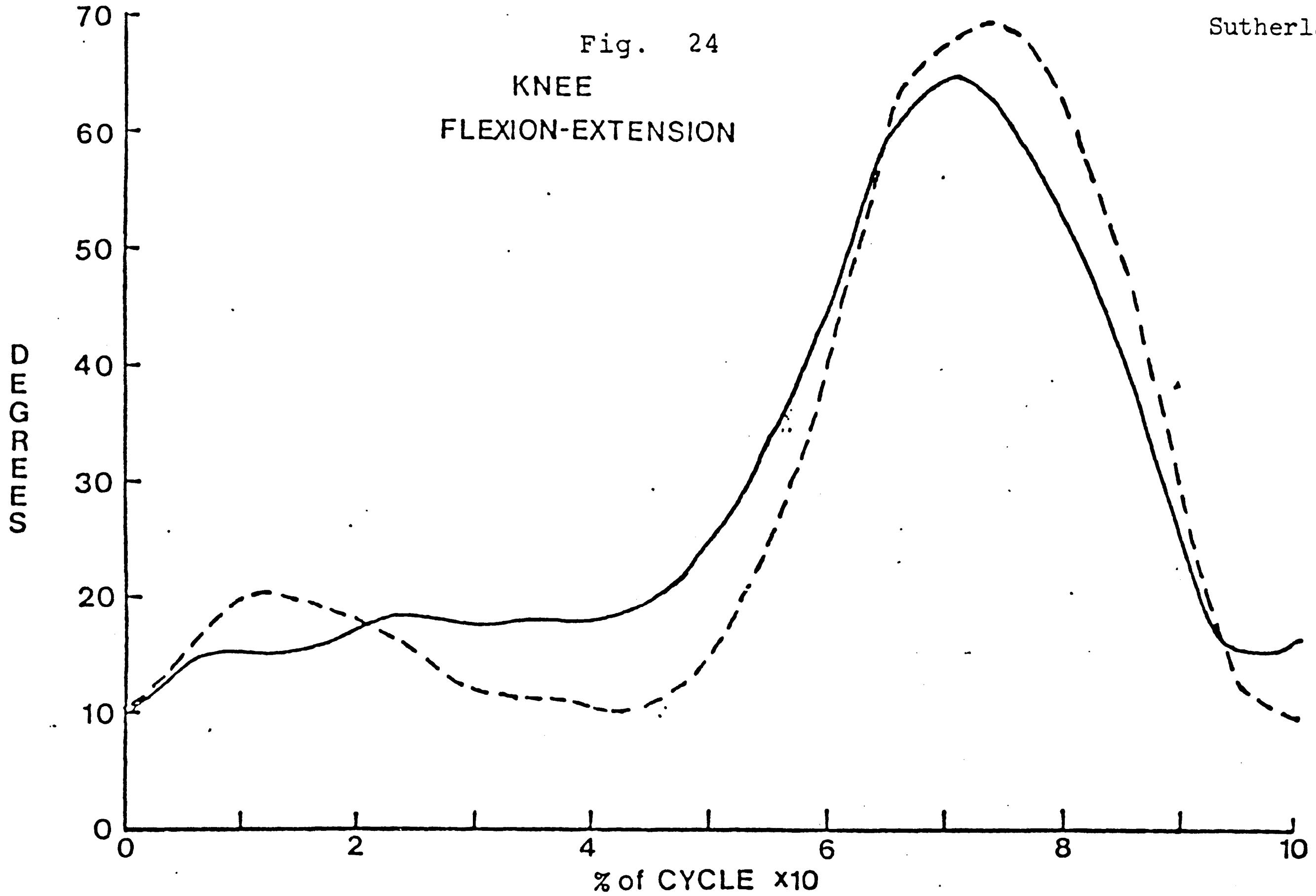
Fig. 24



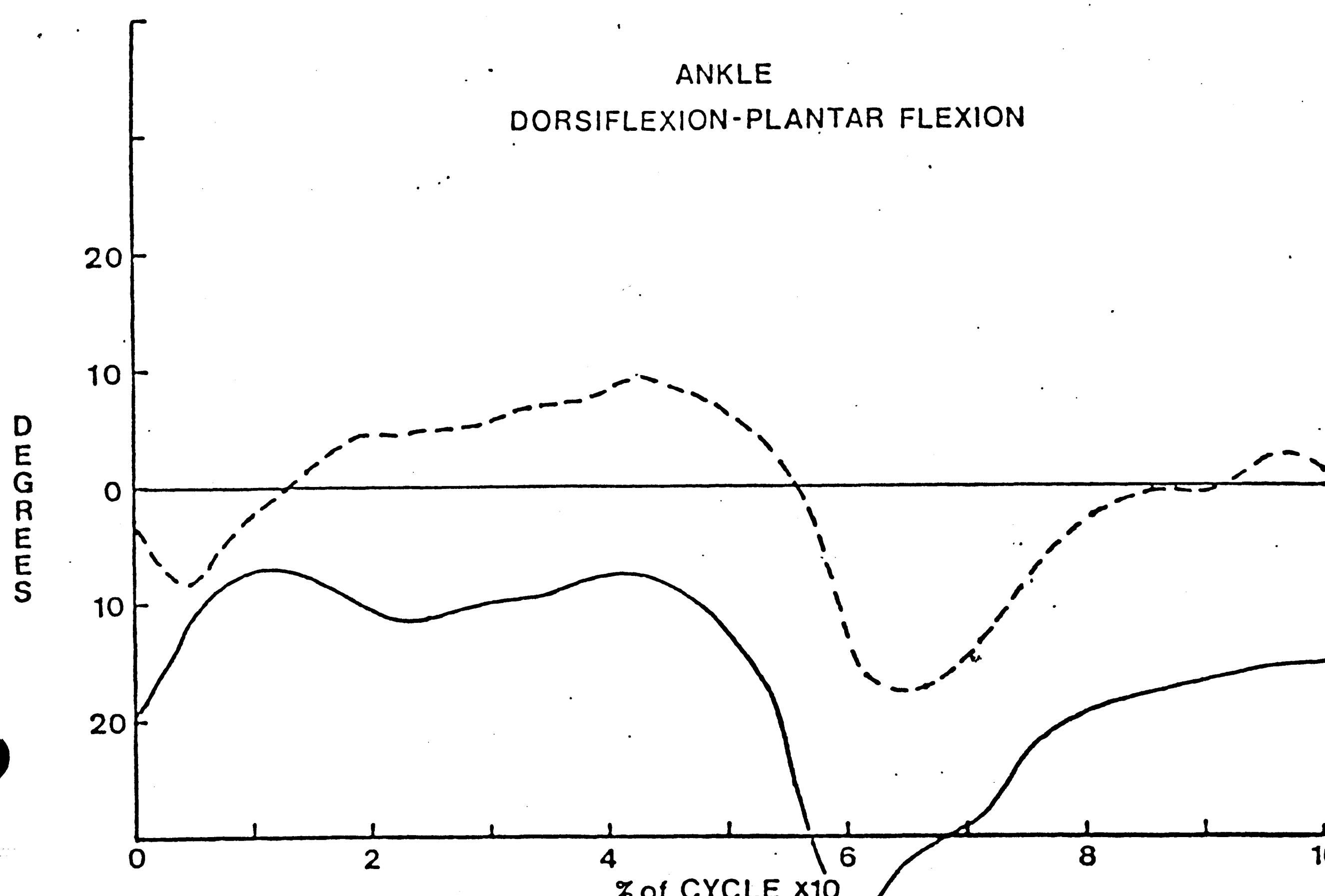


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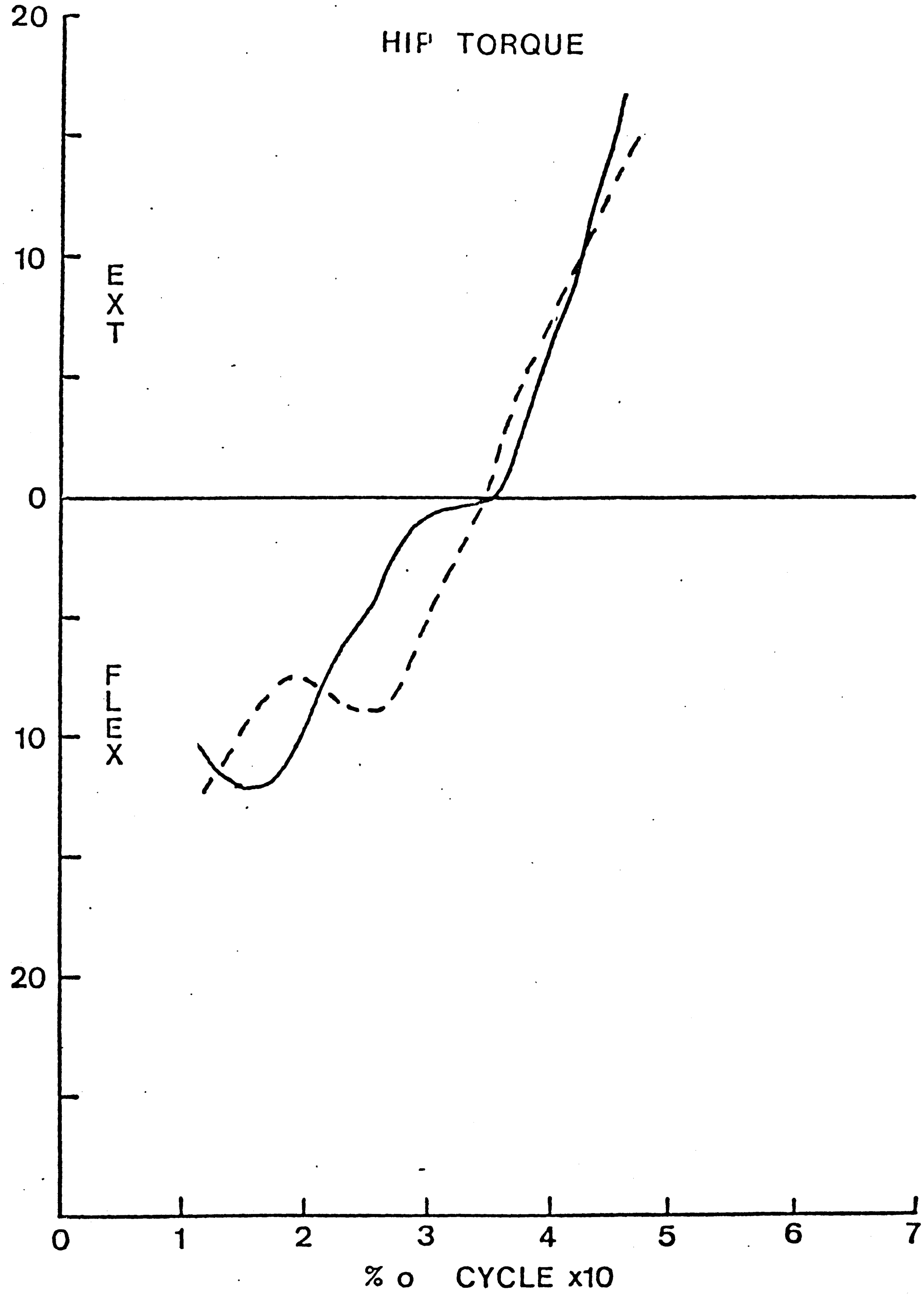
Fig. 25



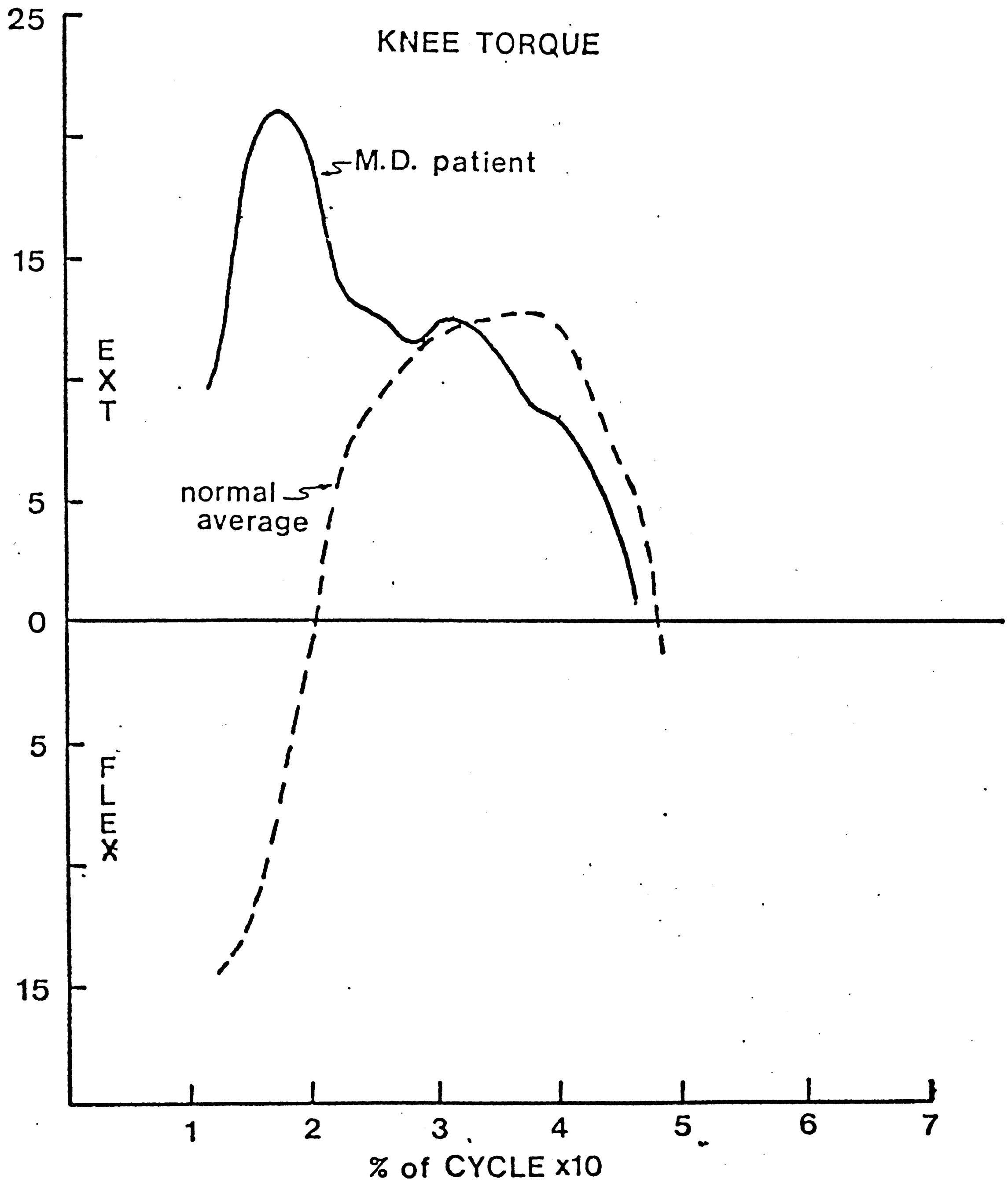
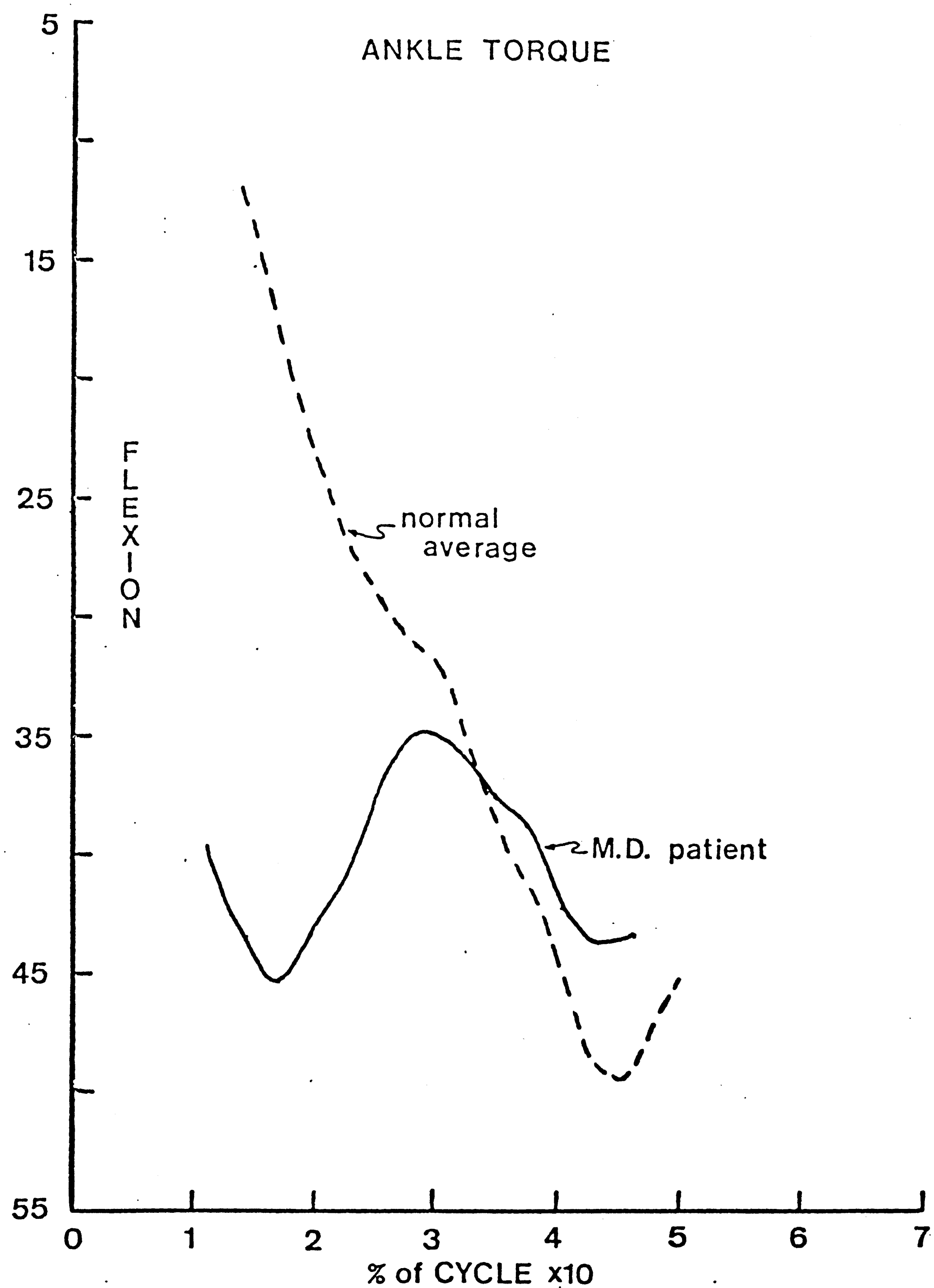

KNEE TORQUE
M.D. patient
normal average
25
15
5
0
5
15
EXT
FLEX
1
2
3
4
5
6
7
% of CYCLE x10

Fig. 27


ANKLE TORQUE
FLEXION
5
15
25
35
45
55
0
1
2
3
4
5
6
7
% of CYCLE x10
normal
average
M.D. patient

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