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Electromyographic gait assessment, part 2: Preliminary assessment of hemiparetic synergy patterns*

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Abstract—The electromyographic (EMG) gait patterns of both lower limbs in 12 hemiparetic patients were studied during the early and late recovery periods. The linear envelopes of surface EMG were ensemble averaged to represent performance. The patients' stride parameters and EMG envelopes were compared to those of normal individuals measured at very-slow walking speeds. Both limbs could have normal or abnormal synergies. The abnormal synergy exhibited by the contralateral limb was almost always a cocontraction. Three different groups of synergies were defined depending on the change in synergy type exhibited by the contralateral limb. Patients who walked at less than a normal very-slow speed during the early recovery period never achieved a normal synergy in either limb. Seventy-five percent of the patients whose walking speed was at least 0.6 meters per second during the early recovery period improved or maintained their gait performance for at least one year.

INTRODUCTION

Although the disturbed motor control of gait in hemiparetic patients has been investigated, very little attention has been given to the time evolution of this control as exhibited by the muscular synergy patterns of both limbs. In fact, almost all of the patients whose studies have been reported in the literature, were more than 6 months poststroke. One unanimous observation has been that there is a great amount of interindividual variation (4,2).

Several general classifications of synergies in the affected limb have been identified. The one which seems most easily identified and which has received the most emphasis is the equinovarus gait (5). Another prevalent synergy is the extensor synergy, defined as a cocontraction of a majority of muscle groups through most of stance phase. Concomitantly, the patients walk much more slowly than normal; speeds around 0.5 m/s are common. The stance phase of the unaffected limb can be 80 percent and be greater in duration than that of the affected limb (1,4).

Although gait is a bilateral and reciprocating phenomenon, only two investigators have reported the synergies of both limbs (1,3). As might be expected the synergies of the unaffected limb differ from normal because they are, at least, compensating for the disturbed control of the opposite limb. There is a tendency for the muscles to have longer durations of activity and to be active simultaneously.

In order to produce more information about the evolution of disturbed motor control, the associated interlimb coordination, and effective therapeutic procedures, a long-term research project has been initiated. The results of the first phase, a behavioral study on a limited number of patients, is reported herein. These results are evaluated with respect to a normative database comprising of the synergy

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patterns of normal individuals walking at hemiparetic gait speeds. The latter database has been reported in Part 1 of this paper (6).

METHODOLOGY

The EMG synergy and foot contact patterns of 12 hemiparetic patients, (5 left and 7 right) were measured bilaterally within two time periods. The first period, the early recovery period, was within 1 week of the time when the patient was able to ambulate independently with a cane. This period occurred within 1 to 10 weeks poststroke. The second period, the late recovery period, was defined as extending from 6 months to 24 months poststroke. This time period is regarded as the period by which the patient's gait has stabilized. Several patients were wearing orthoses during their early-recovery period. These devices were not worn during any of the measurement sessions in order to allow the patients' natural synergy to occur. Assistive canes were always used since they were essential for safety and balance. The EMGs of the tibialis anterior, gastrocnemius, soleus, medial hamstring, and rectus femoris muscles were measured. All data were measured, acquired, and averaged with the same equipment, procedures, and software described in Part 1 with the following exceptions:

1. The subjects were requested to walk at their own comfortable speed; and,
2. The EMGs of each limb were measured during separate walking trials during the same measurement session.

The stride statistics measured from the normal population walking at very-slow speeds (reported in Part 1) were used as a basis for comparison. Normal ranges for stride parameters were defined as being within 2 standard deviations of the average and tabulated.

The LE of the EMGs of the patients were evaluated in two ways. The first was the most direct and meant simply assessing whether or not a particular LE was within 2 standard deviations of a normal profile. The second is more difficult and involves assessing a synergy pattern. For instance, an extensor synergy is exhibited when the extensor muscles are active within the same time period. However, for some muscles this may be the normal time and for others not the normal time. Because of the large variability in hemiparetic EMG gait patterns, the abnormal synergies of both the affected and unaffected limbs were classified according to the criteria established by Knutsson and Richards (2). These types are:

I. Equinus synergy;
II. Paretic synergy, in which 2 or more muscles have no activity or weak activity;
III. Reflex coactivation, with a majority of muscles active throughout most of the same gait periods; and
IV. Complex, seldom-occurring and complicated synergies that do not classify as the other types.

The presentation of the results is organized according to the state of normality of the contralateral synergies in the early and late recovery periods. There are three groupings: A) synergies normal in both time periods; B) synergies normal in only late time period; and, C) no normal synergies.

RESULTS

Stride Characteristics

The stride parameters and time periods of measurement for the patient population are summarized in **Table 1**. The average poststroke times for the early and late recovery periods are 4.4 weeks and 57.5 weeks, respectively.

Table 2 summarizes the stride statistics of normal individuals walking at very-slow speeds. Those patient parameters whose values lie within this range are marked in **Table 1** with an asterisk. The stride characteristics among the patient population are highly variable. For instance, the patients' walking speeds range from 0.08 to 0.84 meters per second (m/s) and stride times range from 0.96 seconds to 4.60 seconds. Approximately 50 percent of these parameters lie within the expected normal ranges for very-slow walking. Some of the stride parameter values are consistent with slow speed walking; for instance, patient JM has a walking speed of 0.83 m/s in the late recovery period.

Table 3 summarizes the distribution of these parameters with respect to the normal ranges for very-slow speed walking. Stride time was most often within these ranges, in 70.8 percent of readings, and speed the least often, in 33.3 percent of readings. Observe in particular that stance phase was almost never less than normal and that single-leg support

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Table 1
Stride Parameters and Measurement Times

Patient Code	Side	Weeks Post	Speed	Stride Time, s	Stance %	SLS %	Step Time %	Foot Contact Type
AD	RT	1	.28*	1.76*	62*	13	45*	N
		84	.33*	2.38*	70*	18	40	EE
CD	RT	3	.64*	1.65*	58*	32*	46*	EE
		17	.23	2.49*	56	26*	44*	EI
JM	LT	3	.70*	1.18*	72*	36*	50*	N-D
		67	.83	1.33*	66*	35*	52*	N
CT	RT	4	.25	1.74*	79	12	48*	N
		83	.20	2.16*	73*	15	38	FF
EB	LT	3	.17	2.26*	95	24	44*	N-D
		70	.51*	1.45*	69*	32*	47*	N
HP	RT	7	.80	1.28*	66*	34*	48*	N
		69	.84	1.2*	64*	37*	50*	N
JT	RT	5	.68*	1.50*	68*	40*	54*	N
		73	.76*	1.12	64*	40*	52*	N
CM	LT	10	.26	.96	79	16	40	EE
		62	.40*	1.48*	79	27*	40	FF
ES	LT	6	.16	4.60	95	10	44*	N
		54	.25	2.34*	75	25*	50*	N
KM	LT	1	.17	3.58	95	5	42	EI
		30	.13	3.24	83	10	46	EI
SC	RT	8	.14	2.56*	79	7	35	EI
		49	.38*	1.60*	80	22	40	EI
VL	RT	2	.08	3.92	87	6	35	EE
		32	.08	3.92	75	10	45	EI

Table 2
Statistics of Normal Stride Parameters at Very-Slow Speeds

Parameter	Average	Standard Deviation	Range
Speed	.55 m/s	0.11 m/s	0.33– 0.77 m/s
Stride Time	1.94 s	0.38 s	1.18– 2.70 s
Stance Phase	65.55%	3.74%	58.10–73.00%
Single Leg Support	33.90%	4.33%	25.20–42.40%
Step Time	50.09%	3.11%	43.87–56.31%

Table 3
Distribution of Hemiparetic Parameters with Respect to Normal Very-Slow Speed Walking

Parameter	Within	Greater	Less
Speed	33.3%	12.5%	54.2%
Stride Time	70.8%	20.8%	8.4%
Stance Phase	45.8%	50.0%	4.2%
Single Leg Support	45.8%	0.00%	54.2%
Step Time	62.5%	0.00%	37.5%

was never greater than normal. Five patients (CD, JM, EB, HP, JT) had all the parameters within normal ranges within one or both time periods. Three patients (CM, KM, VL) had all their parameters outside the normal ranges within one or both time periods.

The foot-contact patterns of the unaffected limbs all had normal sequencing. The affected limbs showed a variety of patterns including normal sequencing (N), observed 42 percent of the time. The most frequently observed abnormal sequence was the equinus sequence (42 percent) in which first contact was made with either the fifth metatarsal (EI) or first metatarsal (EE) head. Two patients placed the foot flat on the walking surface (FF) and two others had a normal sequencing but dragged the large toe during transition from stance-to-swing (N-D).

Muscle Synergy Patterns

The EMG synergies of both lower limbs can be abnormal and both were compared to the normal profiles. In **Figure 1** are plotted the normal EMG profiles for very-slow walking speeds. The hemiparetic synergies are extremely variable and can not be profiled as easily as can the normal patterns. Therefore, two examples of classification will be given and the results of the classification presented. **Figure 2** shows an almost normal contralateral synergy from a patient when he was 2 weeks poststroke. The medial hamstring has more activity during terminal stance than occurs in normal patterns; otherwise, the typical interplay of leg and thigh muscle patterns exists. This synergy pattern is almost normal but is classified as a Type IV since it does not belong to the other categories. Consider the synergy pattern from an affected lower limb in **Figure 3**. All of the muscles are active during most of stance. Only the gastrocnemius lies within the normal bounds. The comparison is made by adjusting the stance phase to a standard of 64 percent. This synergy is classified as a Type III.

In general, within the Type III category, two types of synergies existed; one had the muscles active predominantly during stance, and the other during the transition periods. These were designated as Type III-S and Type III-T, respectively. Thus, the synergy pattern in **Figure 3** is a Type III-S.

The synergy pattern types of both lower limbs for both time periods are listed in **Table 4**. Group A comprises of 3 patients whose contralateral EMGs are normal both early and late. Ipsilaterally they have different synergies and in the later period have either normal or Type I (equinus) synergy. Group B comprises 4 patients. They are characterized by early abnormal and late normal contralateral synergies. Their early and late ipsilateral synergies are mixed and some are normal. The remaining five patients, who make up Group C, all have abnormal synergies. The final ipsilateral synergy is mostly Type III (coactivation), whereas, initially, they were mixed categories. The most interesting aspect is that Group C's contralateral synergies are all Type III, and all except one are stance-phase coactivation type synergies.

Table 4
Synergy Categories for Both Limbs

	Ipsilateral			**Contralateral**	
Code	**Early**	**Late**		**Early**	**Late**
	GROUP A				
AD	IV	I		N	N
CD	III-S	I		N	N
JM	N	N		N	N
	GROUP B				
CT	III-T	III-T		III-S	N
EB	II	N		IV	N
HP	II	N		II	N
JT	N	N		III-S	N
	GROUP C				
CM	II	III-T		III-S	III-S
ES	IV	III-T		III-S	III-T
KM	II	III-T		III-S	III-S
SC	III-T	IV		III-S	III-S
VL	II	III-S		III-S	III-S

DISCUSSION

Although many of the stride parameters are within normal ranges, some are consistent with exceedingly slow locomotion. That is, speeds and single-leg support phases are less than, and stride times and stance phases are greater than, those associated with very-slow speed walking. This is especially true in Group C in which 78 percent of the parameters satisfy those ranges; whereas, in Groups A and B this is true for only 17 and 25 percent of the

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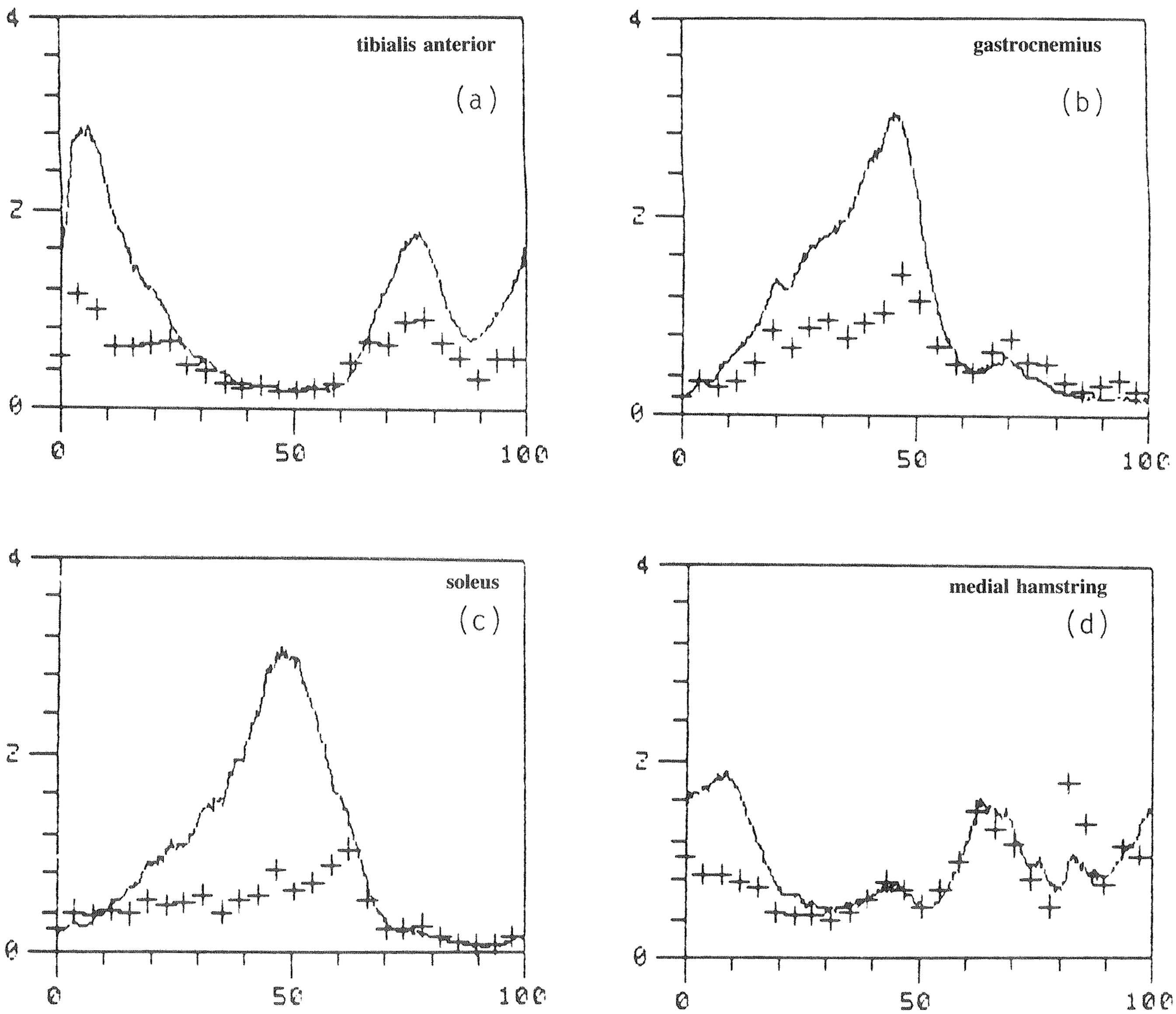

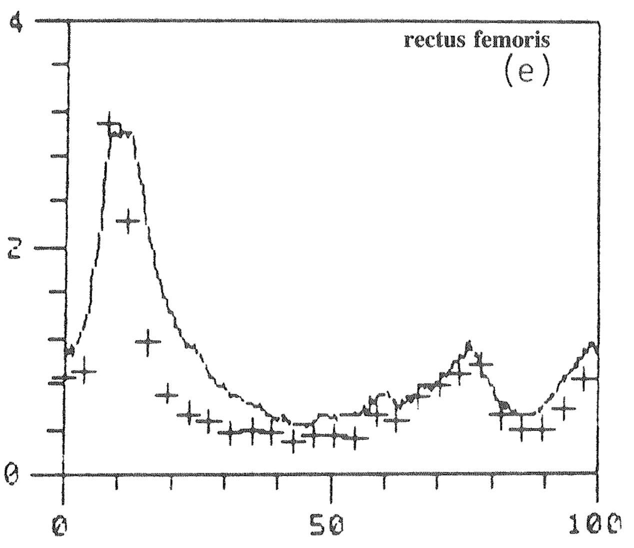

Figure 1.
The EMG profiles, average (−) and standard deviation (+) of LE, of five muscles of normal subjects active at very-slow walking speed are plotted as a percentage of the stride. The muscles are the tibialis anterior (a), gastrocnemius (b), soleus (c), medial hamstring (d), and rectus femoris (e).

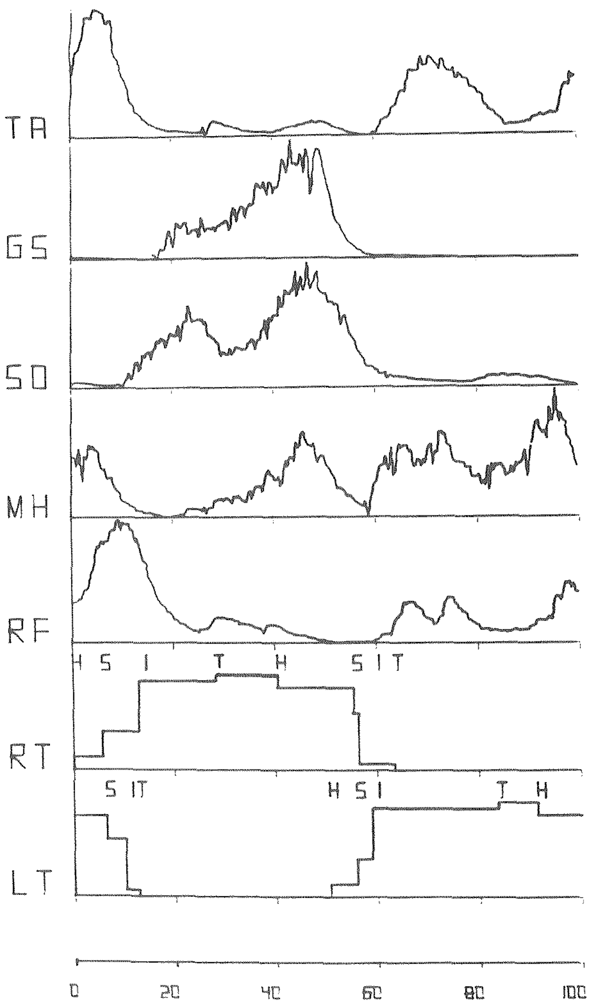

Figure 2.
The EMG and foot-contact patterns of the contralateral lower limb of a hemiplegic patient are plotted as a percentage of the stride. The LE are the tibialis anterior (TA), gastrocnemius (GS), soleus (SO), medial hamstring (MH), and rectus femoris (RF). Contact patterns are for right (RT) and left (LT) feet.

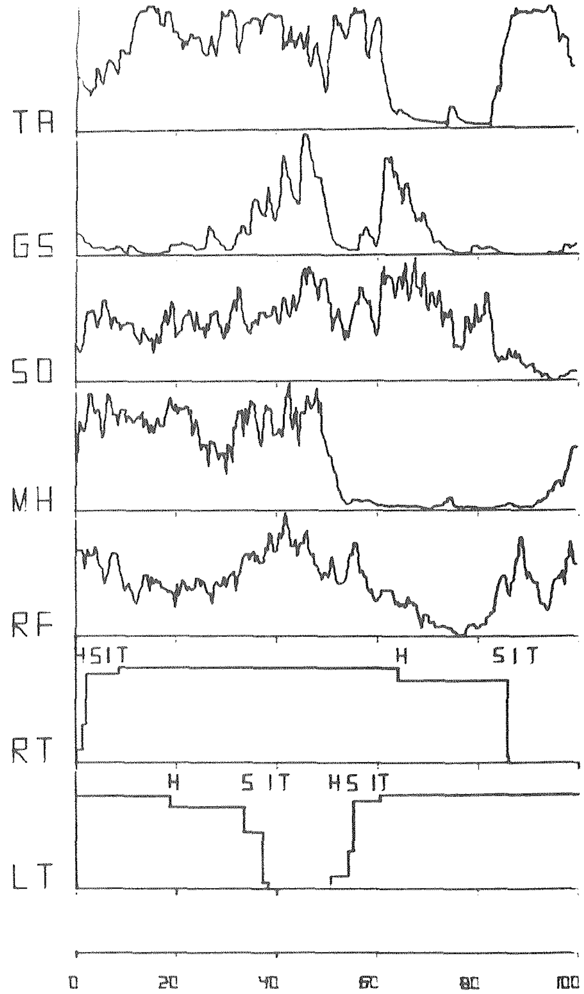

Figure 3.
The EMG and foot-contact patterns of the ipsilateral lower limb of a hemiplegic patient are plotted as a percentage of the stride. The LE are the tibialis anterior (TA), gastrocnemius (GS), soleus (SO), medial hamstring (MH), and rectus femoris (RF). Contact patterns are for right (RT) and left (LT) feet.

parameters, respectively. Examination of the stance and single leg support phases and step times shows, generally, that asymmetric timing exists. With respect to time poststroke, 67 percent of the patients developed increased speeds and decreased stride times. However, this did not always place them within the normal range. Concomitant were increases in single-leg support phase and decreases in stance phase. Several patients, like CD and CT, seem to become worse over time; i.e., their stride parameters changed in more pathologic trends. These observations are consistent with the small amount of published data (1,7).

Some stride parameters and walking speeds correlate strongly with the degree of normality of the synergy patterns. Four patients (JM, HP, JT, EB) whose late synergies were normal bilaterally, also had stride parameters that were within normal very-slow or slow speed walking ranges and were indicative of almost symmetrical gait. Their walking speeds were greater than 0.5 m/s, stance phases less than 70 percent, and single- leg support phases between 32 and 40 percent. Only one of them, EB, walked in the early recovery period with stride parameters outside of a normal range. In Group A the patients' foot-contact patterns were consistent with their muscle patterns. The two equinus gait patients (AD, CD) walked extremely slowly, approximately 0.3 m/s, even though the contralateral synergies were normal and the stance phase was less than 70 percent. In contradistinction, in Group C, not only did the patients have abnormal stride parameters, but 80 percent also had abnormal foot-contact sequencing and not one ever had a normal synergy pattern. The Group B patients were the most normal in the late recovery period. Almost all of the foot-contact patterns had normal sequencing and almost all of the muscle synergies were normal bilaterally.

The contralateral limbs also had abnormal synergy patterns although they were abnormal less frequently than those of the ipsilateral limbs. The abnormal synergies observed were predominantly the stance phase coactivation synergies. Whether these were abnormal because of neurologic insult or biomechanic compensation can not be inferred. However, as shown in Group B patients, there can be a transition from early abnormal to late normal contralateral synergy patterns. This is in contrast to the experience of Group C patients, whose contralateral synergies always remained Type III.

In almost all of the patients as they went from the early to late recovery period, the stance phase decreased toward 64 percent and the single-leg support phase increased. Only the patients in Group B improved in their gait to develop normal synergy patterns and almost normal stride characteristics. Patient JM from Group A was normal in the early recovery period. Presently, from this data, there is only one predictor from early gait performance about possible indicators of late gait performance. If a patient has a walking speed greater than 0.6 m/s within the 3- to 6-week poststroke period, he will most likely stay functional for a year. A much larger database is required to make more definitive and additional conclusions.

SUMMARY

The stride parameters and EMG patterns of both lower limbs in hemiplegic patients were studied during the early and late recovery periods. They were compared to gait performance of normal individuals measured at very-slow walking speed. The synergy patterns were classified either as normal or as belonging to one of four types defined by Knutsson and Richards (2). Both limbs could have normal or abnormal synergies. The abnormal synergy exhibited by the contralateral limb was almost always a cocontraction. Many of the stride parameters were abnormally outside the ranges for normal very-slow walking and were indicative of asymmetric gait. Patients who walked at less than a normal very-slow speed during the early recovery period never achieved a normal synergy in either limb. Seventy-five of the patients whose walking speed was at least 0.6 meters per second during the early recovery period improved or maintained their gait performance for at least one year. More data needs to be gathered in order to determine any correlation between gait performance in the early recovery period and long term potential.

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