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Stability and Velocity in Incomplete Spinal Cord Injured Subject Gaits

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Abstract: We have defined 2 indices describing gait kinematic and dynamic stability. We assessed their values in the gaits of 5 different paraparetic subjects. The indices are correlated to the gait velocity to prove the close relationship between overall gate velocity and stability. Based on stability analysis and certain kinematic parameters, some possible ways of increasing the average gait velocity are explained. **Key Words:** Gait—Analysis—Synthesis—Stability—Velocity—Spinal cord injury.

In the rehabilitation process of spinal cord injured (SCI) subjects, crutches are used extensively to provide the necessary forces for maintaining upright balance and body stability. Such a gait pattern is quadrupedal because the arms with crutches are utilized as the second pair of legs. At least 4 channel functional electrical stimulation (FES) is used for the propulsion of paralyzed lower extremities in the case of complete spinal cord injury (1).

The 3 main drawbacks of such a gait are low average velocity, energy inefficiency, and insufficient propulsion forces in the direction of walking. As it is unlikely for the balance problem to be solved in the near future, the FES enabled gait will remain quadrupedal, and we are therefore dealing with the problem of how to improve the existing 4 point gait (2).

Stability, in terms of preventing the subject from tipping over, is a crucial problem in the gait synthesis. The present FES paraplegic gait utilizes a creeping gait pattern known as crawl, which exhibits superior static/kinematic stability properties. Such a system can remain in a statically/kinematically stable state for an arbitrary amount of time. The result is that the gait can be arbitrarily slow, but the maximum velocity is limited (3). A system is in a statically/kinematically stable state if the vertical projection of the center of gravity (PCOG) on the ground plane is inside the supporting area.

In faster gaits dynamic stability becomes important. The system is in a dynamically stable state when it can recover a statically/kinematically stable state without raising any of the supporting legs or placing any of the swinging legs on the ground. In contrast, a dynamically unstable state requires a walking mechanism to make at least one step more in a limited amount of time; therefore, the system dynamics dictate the step length and cadence and also the average gait velocity. In this case, the minimum velocity is limited (4).

In this paper we discuss the mutual dependence of crutch-assisted gait velocity and stability from a biomechanical perspective.

MATERIALS AND METHODS

The FES assisted gait of SCI subjects is much more complicated then a hypothetical walking machine. The gait direction and velocity change almost erratically during the gait cycle. Also the foot-ground contacts are finite area surfaces and not just simple points as usually treated. Therefore, we defined a relative kinematic stability index as

$$\mathrm{RKSI}_1 = \frac{d(PCOG,CS)}{|d(TSE,LSE)|/2} \tag{1}$$

The numerator is the distance from the patient center of gravity (PCOG) to the supporting area edge in the direction of the instantaneous velocity of the center of gravity (COG). The center of the supporting area (CS) is the midpoint between the leading

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supporting area edge (LSE) and the trailing supporting area edge (TSE). The points CS, LSE, and TSE are placed in the supporting area with respect to the instantaneous PCOG position and gait direction. It is important to stress that all the defined points but PCOG change if the instantaneous COG velocity changes, which in turn also affects the stability index $RKSI_1$ (5). Function d in Eq. 1 denotes the distance between the 2 points. Distance d in the numerator of Eq. 1 is positive if the PCOG is behind the center of the supporting area (CS) and vice versa. The system is in a kinematically stable state if $RKSI_1$ in [−1,1].

The knowledge of COG movement and the supporting area shape/size is required to determine the subject's dynamic stability. The decisive factor is the maximal possible breaking force, which is limited by the fact that the ground reaction force (GRF) origin or center of pressure (COP) is always inside the supporting area, and it always points towards the COG. If the velocity v_{COG} of the system exceeds critical velocity, then the system is in a dynamically unstable state. We therefore define a simple absolute dynamic stability index:

$$\mathrm{AVI} = \sqrt{\frac{g}{z_{COG}(t)}}d(PCOG,LSE)(t) - v_{COG}(t) \quad (2)$$

g is the acceleration of gravity and $z_{COG}(t)$ is the height of the COG above the ground level. If the index AVI is positive, the system is in a dynamically stable state and vice versa.

If we assume the gait is regular, then the average gait velocity is kinematically defined as

$$v = \frac{R}{t_t}\left(\frac{1-\beta}{\beta}\right) \quad (3)$$

R is stroke pitch, which is approximately equal to the step length, β is leg duty cycle, t_t denotes leg swing or transfer time, and T is the gait period. The critical value of β for quadrupedal gait is 0.75 (3), which still enables a kinematically stable gait when at least 3 extremities are on the ground.

RESULTS

The described methods were applied to the gaits of 5 different incomplete SCI subjects. The OPTOTRAK (Northern Digital, Inc., Waterloo, Ontario, Canada) motion analysis system provided necessary body segment position data, which was then fed into the full dynamic model of crutch supported gait. The results are dimensions of supporting area and COG position and velocity. Calculation of the kinematic and dynamic stability indices is then trivial. The whole analysis was performed for walking on a flat, level, and hard surface.

Table 1 presents a few details on the tested subjects. If a single FES channel is used, it triggers the flexion withdrawal reflex. If 2 channels are used, the second one stimulates the knee extensors. Table 2 shows the mean, minimum, and maximum values of the kinematic and dynamic stability indices. Table 3 presents the mean values of the kinematic parameters with significant influence on gait velocity.

DISCUSSION

Our primary goal is increasing the average velocity in FES and crutch assisted gait, and from this perspective, we discuss the results. The relative kinematic stability index $RKSI_1$ increases with increasing gait velocity, which means that subjects subconsciously partially compensate their body dynamics. Their COG is on average shifted backward from the center of the supporting area with increased gait velocity. This COG shift is small but detected in all tested subjects. An exception to this rule is Patient O4 who was utilizing a different gait pattern as he was moving both crutches forward simultaneously.

The minimum values of $RKSI_1$ are never less than −1, which means that the COG is never ahead of the supporting area with regard to the instantaneous direction of walking. Contrary to the normal biped gait, such kinematically unstable states obviously never occur in FES assisted gait. However, in Patients O1 and O2 the maximum value $RKSI_1$ exceeds 1, which indicates kinematically unstable states. In such cases the COG was behind the supporting area. The rather high maximum value of $RKSI_1$ is due to a very small denominator with regard to the definition in Eq. 1. In this particular moment, the supporting area length in the instantaneous direction of walking is very small.

The average and minimum values of the absolute dynamic stability index AVI are positive. Therefore, the subjects are always in dynamically stable states. As a result, they are never forced to perform any action and they can walk arbitrarily slow. The minimum value of AVI is as low as 0.2 m/s. This is the

TABLE 1. *Tested subjects*

Patient	Code	Sex	Injury	FES	Time since injury
FG	O1	M	C4–5	no	5 months
LG	O2	M	C6–7	1 ch. right	3 years
IF	O3	M	C5	1 ch. right	6 months
FV	O4	M	C6–7	2 ch. right	4.5 months
MT	O5	F	T4–5	2 ch. left and right	6 years

TABLE 2. *Stability indices*

Patient	$RKSI_1$			AVI (m/s)		
	Mean	Min	Max	Mean	Min	Max
O1	0.307	−0.385	1.115	2.068	0.520	3.782
O2	0.170	−0.464	6.116	1.955	0.434	4.604
O3	0.061	−0.532	0.597	1.648	0.337	4.056
O4	0.059	−0.589	0.770	1.770	0.237	3.603
O5	0.009	−0.539	0.643	2.536	0.623	5.691

minimum velocity increase required to at least occasionally slip into a dynamically unstable state. However, an interesting fact is that the minimum value of AVI is not at all correlated to the gait velocity.

We can deduce that kinematic stability and dynamic stability are mutually independent. Therefore, the system can be dynamically stable at the same time it is kinematically unstable and vice versa. This was the case for Patients O1 in O2 because they were, according to the $RKSI_1$, in kinematically unstable states but, according to the AVI, in dynamically stable states. The average value of AVI was close to 2 m/s in all tested subjects. For this amount, the velocity should be increased on average to achieve dynamically unstable states with unchanged gait patterns and supporting areas. However, it is not possible to do so.

Stroke pitch R and leg swing time t_t are kinematic parameters directly influenced by the FES system and number of channels utilized and can therefore be changed most easily by adapting the existing stimulation patterns.

However, an important observation is that the leg duty cycle β is on average close to the critical value of 0.75 as defined by Eq. 3. This means that it is no longer possible to increase the gait velocity unless β is decreased below its critical value. However, this implies that 2 point states are introduced into the gait. In such moments, only 2 extremities are on the ground, which implies at least kinematically unstable states. In such a gait, the extremity duty cycle β is more than 0.5. Table 4 shows the actually assessed (v) and theoretically possible v_t velocities for kinematically/statically stable gait ($\beta \geq 3/4$) and for 2 point gait including unstable states ($\beta \geq 1/2$) assuming the stroke pitch R and leg swing time t_t are unchanged.

TABLE 3. *Kinematic parameters*

Patient	t_t (s)	β	R (m)	v_{COG} (m/s)
O1	0.780	0.743	0.571	0.245
O2	1.243	0.667	0.548	0.182
O3	0.759	0.790	0.353	0.137
O4	0.570	0.797	0.444	0.200
O5	1.278	0.830	0.299	0.051

TABLE 4. *Assessed and theoretically possible velocities*

Patient	v (m/s)	v_t (m/s)	
		$\beta = \frac{3}{4}$	$\beta = \frac{1}{2}$
O1	0.245	0.244	0.732
O2	0.183	0.147	0.442
O3	0.138	0.155	0.465
O4	0.200	0.260	0.779
O5	0.047	0.079	0.236

It is obvious that only the gait with unstable states where $\beta < 3/4$ can result in a significantly faster gait. Because kinematic and dynamic stability are mutually independent, we can first try to introduce kinematically unstable states in the present FES gait, which in most cases consists of kinematically and dynamically stable states. Patients O1 and O2 demonstrate that this is possible. However, this also implies a change in gait control. In a gait consisting of only stable states, kinematics provide enough information to ensure successful and stable control. If kinematically unstable states are introduced, then the control system must be able to recognize at least the body inertial properties. If dynamically unstable states are introduced, then the control system must be able to deal with full body dynamics and has to operate in real-time.

In our case the control system is the SCI patient himself. He is now trained for the gait consisting of only stable states, and therefore introducing any kind of unstable states would require a prolonged and new approach to gait training, teaching the patient a new type of control. The task would of course be much simpler if in the beginning only kinematically unstable states are introduced followed by dynamically unstable states. Kinematically unstable states can already improve the gait velocity, but a significant velocity increase and possibly a drop in energy consumption would result only from dynamically unstable states.

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