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Stability analysis of four-point walking

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Abstract

The aim of the experiment reported here was to determine the static and dynamic stability of two-point stance phases when walking on hands and knees at different speeds. In addition, we defined the methods and predicted the consequences of including two-point stance phases into crutch assisted functional electrical stimulation (FES) walking. Crawling on hands and knees was performed at three speeds by five healthy male persons. With twelve joint-position markers placed on the subject, we determined two stability indices for every instant of gait. We analysed the peak values of these two indices during the two-point stance phases. The results indicate that we have to ensure the proper position of the centre of gravity to increase the speed of walking. To reach speeds, lower than 0.6 m/s, it is not necessary to include statically unstable phases. The shift of the centre of gravity towards and across the leading stability edge can result in getting into the dynamically unstable state. Considering the results we can effectively introduce two-point stance phases into crutch assisted FES walking and therefore increase the speed and energy effectiveness of walking

Keywords: Four-point walking; Static stability; Dynamic stability; Functional electrical stimulation

1. Introduction

The walking of paraplegic persons assisted by functional electrical stimulation (FES) is considerably slower and less effective than walking in a non-disabled person. The average speed achieved by a paraplegic subject is about 0.15 m/s while a healthy person walks normally at about 1.5 m/s [1]. The basic objective of any locomotor system is to move the centre of mass of the whole body forward from the current position to a new location. In our simple reciprocal crutch-assisted FES gait, this is accomplished by the arms and preserved trunk muscles. Such unnatural transfer of the body forward is the main reason for the low energy efficiency of the present FES gait [2].

Crutch assisted FES walking consists only of four and three-point stance phases but recent research has shown that introducing two-point stance phases into the walking sequence could increase the speed and energy effectiveness of walking [2]. Two-point stance phases or unstable states represent the passive phase of walking where the centre of body is gravity-driven in the direction of progression. When comparing locomotion on hands and knees with crutch assisted FES walking of paraplegic persons, the hands correspond to the crutches and the knees to the feet. The most adequate matching of both locomotion patterns was observed at the lowest velocities of human crawling. At the speed of 0.14 m/s, the duration of the crawling cycle was 3.1 s while the duration of the crutch assisted FES gait cycle was 3.3 s. The hands support ratio was 80% of the crawling cycle while the corresponding crutch support ratio was 82% of the gait cycle. The knees support phase lasted for 75% of the crawling cycle while the corresponding foot support phase lasted for 78% of the gait cycle. By replacing the two-point stance phases in the crawling pattern with corresponding four-point stance phases, the pattern of the present FES assisted walking in completely paralysed paraplegic subjects is obtained. Since the time parameters of slow crawling conform well to timing of the FES and crutch assisted walking of paraplegic persons, crawling on hands and knees can be considered an appropriate model for crutch assisted FES walking [3]. Recent

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investigation showed that unstable states, observed in human crawling on hands and knees, should be included into the FES and crutch aided walking scheme [3]. For evaluating the stability of four-point gait that includes unstable states, besides statics and kinematics, we also considered complete dynamics of the walking system.

The main purpose of this paper was to determine the static and dynamic stability of crawling on hands and knees in two-point stance phases at different velocities. Our aim was to define the methods for including the two-point stance phases into the crutch assisted FES walking.

Some investigations in the past have already discussed crawling on hands and knees at different speeds of gait. It has been examined how humans, as animals unaccustomed to four limbed locomotion, adapted their crawling on hands and knees to increases in speed [6]. One of the adaptations to speed in four-limbed locomotion, as they reported, is to change the pattern of inter-limb coordination that defines a style of gait. Introduction of the two-point stance phases into the crutch assisted FES walking, as we propose in this article, is an example of such adaptation.

Kinematics and dynamics of crawling gait and crutch assisted FES walking have been described in detail by some other researchers [3,4,6,7]. The data presented there and their conclusions can be useful for describing the general characteristic of the crawling gait pattern. Along with their findings, our results provide a substantial material for better understanding of the issues associated with stability in four-limbed locomotion and their application to crutch assisted FES gait and the design and control of walking machines.

2. Theoretical background

As shown in the Fig. 1 supporting area in a selected phase of gait is defined as the minimum convex set of points in the ground plane such that all extremity contact points are contained [5].

2.1. Static stability

For the situation shown in the Fig. 1 and from the definition of a statically stable system by McGhee, we can define the dimensionless relative static stability index (RKSI) [4]:

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

where d designates the distance between points in parenthesis. The leading stability edge point (LSE) is the intersection point of the supporting area leading edge and the line from projection of centre of gravity (PCOG) in the direction of the PCOG velocity vector. The trailing stability edge point (TSE) is the equivalent point at the trailing supporting area edge. The centre of stability area (CS) is the midpoint between LSE and TSE. A locomotor mechanism is statically stable if PCOG is inside the supporting area. In our case this is true only if RKSI $\in[-1, 1]$.

2.2. Dynamic stability

The approach used in the previous section is adequate only for multipoint slow walking where dynamic components have no significant influence. For faster speeds this approach is not appropriate and we need to consider the dynamic stability of the system. To define dynamic stability, we translate the problem of stability into the problem of comparing the momentary speed and the critical speed. For every instant of gait, we can define the critical speed using Eq. (2) [4]:

$$v_r(t) = \sqrt{\frac{g}{h}}\, x_r(t), \tag{2}$$

h designates the momentary height of the center of gravity (COG), g belongs to the gravity acceleration, $x_r(t)$ is the momentary distance between PCOG and LSE. The critical speed $v_r(t)$ is that maximal speed when the mechanism is still dynamically stable. The difference between critical and momentary speed can be used as an estimation of dynamic stability [1].

We can define the relative index of dynamic stability (RVI). The index presents the dynamic stability depending on the momentary speed of walking [4]:

$$\mathrm{RVI} = \frac{v_r(x(t)) - v(t)}{v(t)} \tag{3}$$

The system is dynamically unstable if the relative index of dynamic stability has a negative value. Positive values of RVI describe a dynamically stable system, when the system is dynamically stable. Progression can be stopped without changing the momentary position of the hands or knees.

3. Methods

The kinematic assessment of human crawling was performed by the use of contactless OPTOTRAK measuring system (Northern Digital Inc., OPTOTRAK/3010, Waterloo, Ontario N2L 3V2, Canada). Our measuring system consists of two precalibrated position camera systems which permit measurement of 3D marker coordinates bilaterally. For every test person, we had to define both indices of stability for every instant of gait. These indices are derived from supporting area, position and velocity of center of mass and mass itself. To define the necessary parameters, we had to place 12 OPTOTRAK markers at the estimated anatomical positions of both wrists, ankles, shoulders, foots, knees and hips as shown in Fig. 1. The OPTOTRAK system allowed us to acquire data at 100 Hz sampling rate and with accuracy of 0.35 mm. The OPTOTRAK data were collected and checked with a PC computer and further processed with commercial Matlab software and custom written subroutines.

4. Results

Crawling on hands and knees was assessed in five young (average 23 year) men of average height of 174 cm. The subjects were asked to crawl with normal, slow and fast speed. Doing so, we obtained gait patterns of slow, normal, and fast gait for each of the test persons. Mean values of slow, normal and fast crawling are 0.38, 0.59 and 0.82 m/s, respectively. Standard deviations of slow, normal and fast crawling are 0.14, 0.02 and 0.15 m/s, respectively.

Indices of stability were determined for every instant of crawling on hands and knees. As an example, the diagram of index RVI and the support-sequence diagram for normal speed crawling are shown in Fig. 2.

With the help of support-sequence diagrams, describing the duration and timing of contact of each extremity with the floor, we determined the time interval of the two-point stance phase when one hand and its contralateral knee were on the ground, as shown in Fig. 2. During the two-point stance phase, both indices have a clearly expressed peak values that occur just prior to the changes from two-point stance phases to three- or four-point stance phases.

Our further analysis is based on these peak values of indices RKSI and RVI. For each one of the five test persons, we determined both peak values of RKSI and RVI at three different speeds of gait. Mean values and standard deviations of RKSI are presented in the top diagram in the Fig. 3. Value -1 of index RKSI is the boundary between static stability and static instability.

The values of RKSI index for slow crawling are inside the stability range, as shown in top diagram in the Fig. 3. This means that PCOG of all test persons was inside the supporting area. Because RKSI is negative and close to -1, we can say that the PCOG was close to the LSE. During crawling with normal speed, the values of RKSI index are on the boundary between stable and unstable region. We can assume that the speed of 0.6 m/s is the maximal speed of crawling on hands and knees that can be achieved using only statically stable phases, without introducing statically unstable states into the gait sequence. At high speed of crawling on hands and knees, PCOG was outside and in front of the supporting area and the values of RKSI were therefore inside the instability region as shown in top diagram in the Fig. 3.

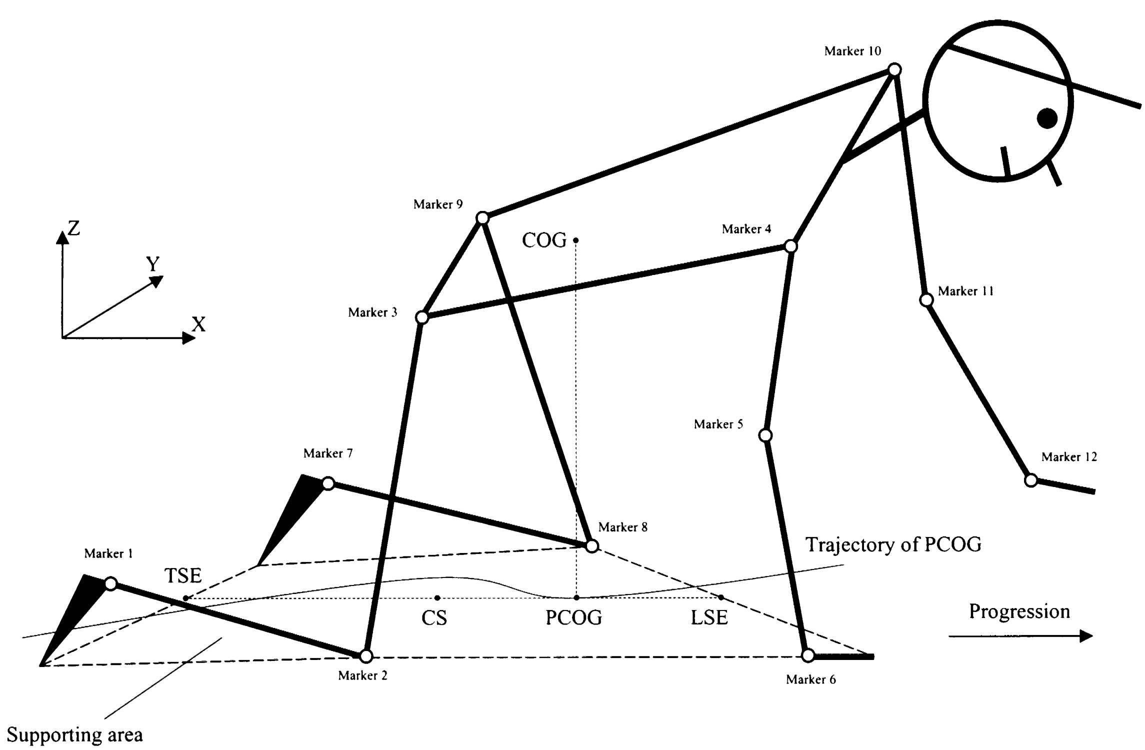

Fig. 1. Crawling person and placement of the 12 measurement markers at the estimated anatomical positions of both wrists, ankles, shoulders, foots, knees and hips. Dashed lines form the supporting area on which the following four points are defined: leading stability edge point (LSE), trailing stability edge point (TSE), centre of stability area (CS) and the projection of centre of gravity (PCOG).

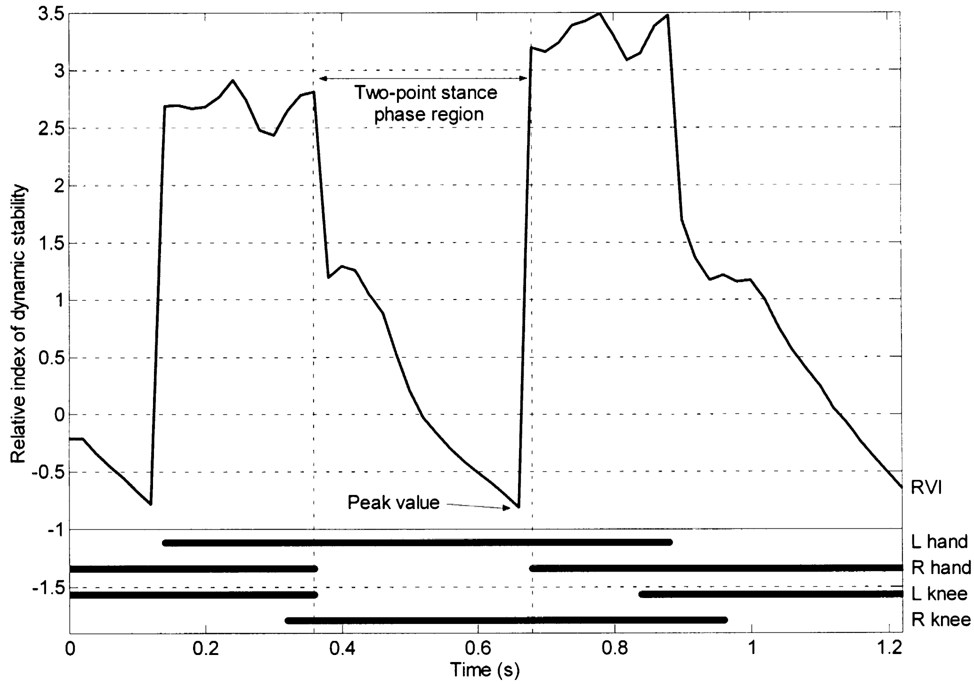

Fig. 2. The diagram of relative index of dynamic stability (RVI) as a function of time and the support-sequence diagram for normal speed crawling. Vertical dashed lines limit the two-point stance phase interval. Bold lines at the support-sequence diagram represent the time interval when a given hand or knee is in contact with the ground.

The bottom diagram in the Fig. 3 shows means and standard deviations for the index of dynamic stability as a function of speed. The abscissa is the boundary between dynamically stable and unstable region. From the bottom diagram in the Fig. 3 we can see that only slow crawling is dynamically stable in the observed period of time, while normal and fast crawling are dynamically unstable. The value of the RVI index reveals beside the stability of the system also the measure of stability, hence, despite different speeds, normal and fast crawling were shown to be almost equally dynamically unstable.

5. Discussion

Our goal was to show the reasons and the consequences of increasing the speed of four-point walking and to provide the methods to increase the average velocity in crutch assisted FES gait, and from this perspective, we discuss the results.

Test persons were in a statically stable state during the two-point stance phases of slow crawling on hands and knees. The value of RKSI index reflects that the PCOG was near the LSE in the observed moment. Such walking enables maximal stability and the possibility to bring the walking system to a standstill in every moment. On the other hand, this kind of gait does not provide the exchange between kinetic and potential energy needed for higher energy efficiency. This kind of four-point walking is comparable to the present crutch assisted FES walking.

When the speed of crawling on hands and knees was around 0.6 m/s, the test persons were on the boundary between static stability and instability. The PCOG was over the LSE. In that same moment, the test persons were in the dynamically unstable state. In this situation, the test person must make at least one additional step to come to a standstill. For this kind of walking we can say that it uses gravitational forces for moving the centre of body forward. This kind of walking is more energy efficient than slow walking which is statically and dynamically stable.

In the observed moments, the fast walking pattern was statically and dynamically unstable. PCOG was in front of the LSE. While walking fast, the test person 'threw' himself forward and transformed the potential energy into kinetic energy. The shift of COG forward was the largest during the statically and dynamically unstable two-point stance phases.

In crutch assisted FES walking the PCOG of paraplegic person is behind the centre of the supporting area from 70 to 90% of the gait cycle [4]. Paraplegic subjects walking with the help FES subconsciously keep their COG back and therefore stay dynamically stable. If we want to increase the speed of gait by introducing the two-point phases, we have to shift the COG forward towards the LSE. To increase the speed of walk-

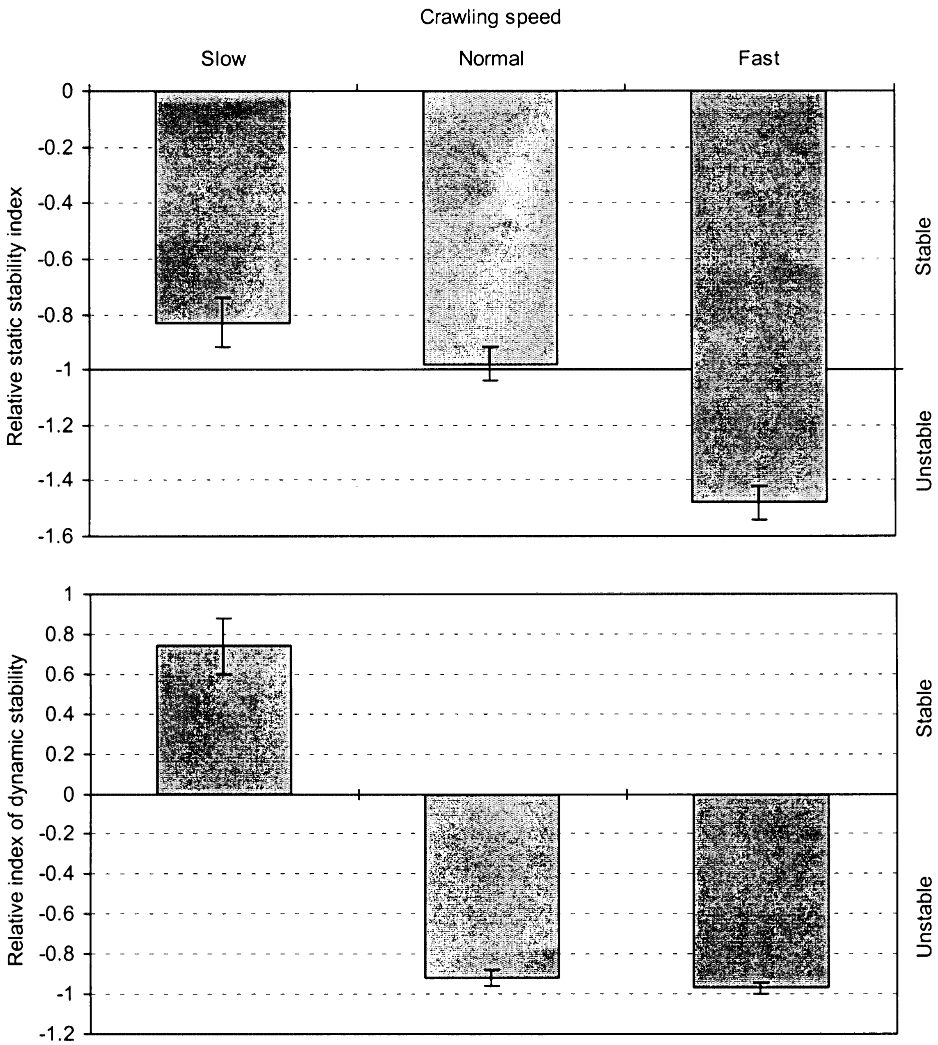

Fig. 3. Average values and standard deviations of relative static stability index (RKSI) and relative index of dynamic stability (RVI) at different speeds. Value −1 of relative static stability index is the boundary between static stability and static instability. The abscissa in the bottom diagram is the boundary between dynamically stable and unstable region.

ing towards 0.6 m/s, we have to shift the COG towards the LSE. Doing so, we remain in a statically stable state. To increase the speed over 0.6 m/s, the COG should be shifted in front of the supporting area. The consequence of shifting the COG forward is a dynamically unstable state. The system that is in a dynamically unstable state cannot recover a statically stable state without raising any of the supporting legs or placing any of the swinging legs on the ground. In this case, the system dynamics dictate the step length, cadence and also the average gait velocity. The introduction of dynamically unstable states into the four-limbed gait demands high accelerations and speeds of extremities. Our next goal should be to determine the relationship between the mobility of extremities and the top speed of walking.

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