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A COMPUTERIZED METHOD FOR CLINICAL GAIT ANALYSIS OF FLOOR REACTION FORCES AND JOINT ANGULAR MOTION

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ABSTRACT. A method for clinical studies of ground reaction forces during gait is presented. A walkway consisting of two force measuring platforms, each five meter long, allows the recording from several consecutive steps from both feet. Signals from photocells and goniometers have been added and a microcomputer system for on line recording and processing have been developed. The accuracy of the system is tested.

Key words: Gait analysis, method, force plate walkway, electrogoniometer, hip, knee

Attempts are being made at a better understanding of walking or at finding significant parameters, that distinguish different types of gait disturbances and judge the effectiveness of treatment.

MEASUREMENT OF GROUND REACTION FORCES

The vertical force was calculated first by Fischer in his and Braune's work: "Der Gang des Menschen" (3). Elftman (6) registered the three force components between foot and ground by using a mechanical force plate. Using a five meter long force plate walkway Rydell (11) registered the vertical and horizontal fore and aft forces in his monograph on forces acting on a femoral head prosthesis. The same year Skorecki (13) presented his "Gait Machine", a system based on elastically deformable diaphragms actuating light beams and used by Charnley. These two methods are still the only known means of recording the ground reaction forces of both feet from several consecutive steps. The small Kistler force plate (9) with piezo electric force transducers and capable of measuring very rapid movements has become the most utilized method of recording ground reaction forces.

The ground reaction forces as well as all other variables in gait analysis vary with changes in walking speed as described by Andriacchi (1) and Murray (10) among others. Therefore supplementary measurements are necessary to register average velocity, step rate and step length. To determine the internal joint forces the ground reaction forces must be calculated together with kinematic registration of the body segments. The Enoch system described by Gustafsson & Lanshammar (7) combines information from the Selspot system (15), the Kistler force plate, body segment data and time–distance parameters to get information on the internal forces such as the direction of the force vectors and their distances from the joints. The concept "Force Line Visualization" indicating the alignment of the ground reaction force vector with the supporting limb to be visualized was described by Cook (5) and has proved to be a clinical instrument for joint load estimation.

AIM OF STUDY

The aim of this study is to introduce a practical method by which a quantitative analysis of gait can be made of: 1) the time and distance factors, 2) the sagittal angular movement of the hips and knees, 3) the vertical ground reaction forces.

It is assumed, that this method will provide results, that reflect clinical findings; – will be sensitive enough to distinguish differences in functional ability; will be a clinical tool in evaluating individual patients. The clinical applicability may make it easy to accumulate a normative data base.

METHOD

Force Plate Walkway

Rydell (11) described the force plate walkway, constructed in cooperation with Hirsch. The walkway offers an evaluation of the forces acting on a femoral head prosthesis which could be related to the different phases of gait.

Original design

The walkway consists of two five meter long force measuring platforms, twenty cm wide and two cm apart. Thus

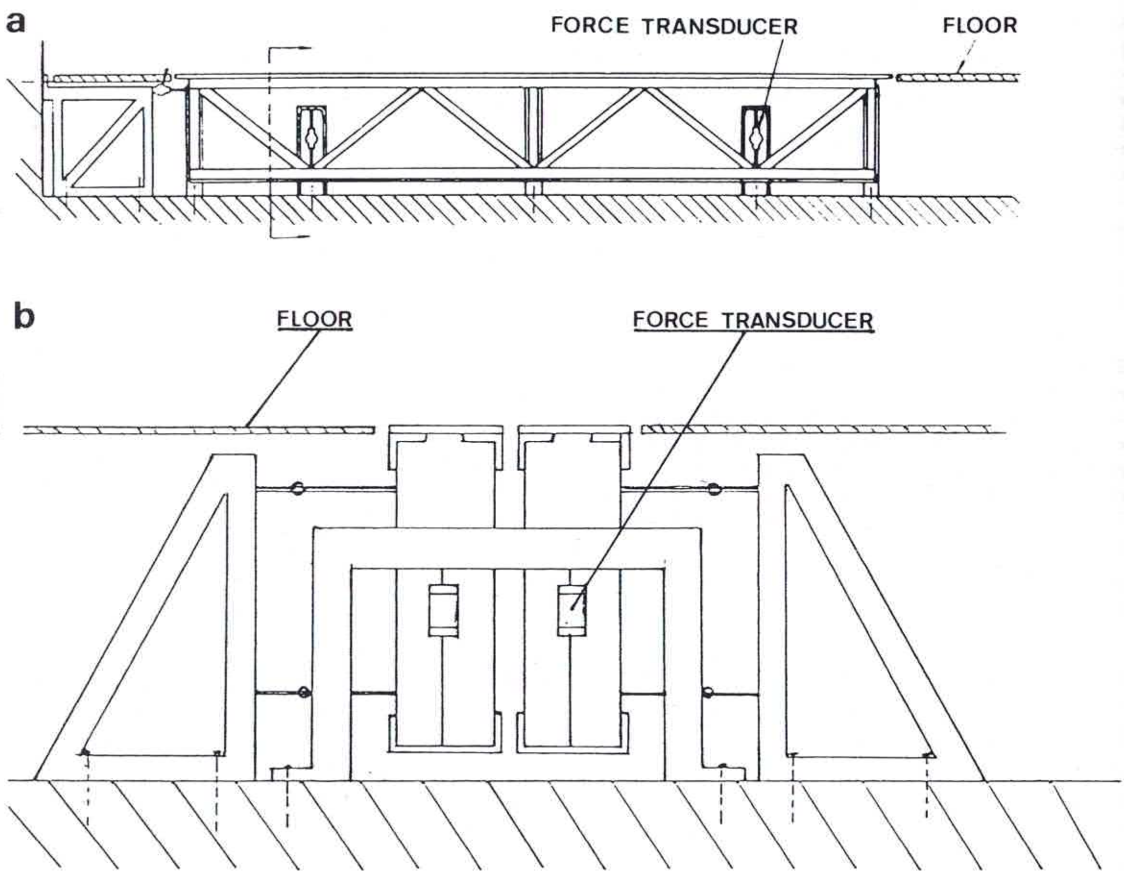


Fig. 1. Construction of walkway. (*a*) Side view Rydell (11), (*b*) front view.

several steps can be continuously and separately analyzed. Each platform with an approximate weight of 30 kg consists of two U-beams with their hollow faces joined together by flat bars, thus increasing the stiffness. Each platform is suspended via strain gauge force transducers from two inverted U-supports set in concrete on the solid ground (Fig. 1). In order to place the surface of the force plates at floor level, the floor was raised. At each end of the walkway there is free floor space to allow the subject to walk at a constant speed on the walkway. Each force plate has two force transducers, sensitive to changes in the vertical force. (VFT = vertical force transducer.) The signals from these two were added together to get the total vertical force from each force plate. Another force transducer sensitive to changes in the horizontal fore and aft forces (HFT) was connected to one end of each platform. For feeding, balancing and calibrating the force transducers, four Bofors BK-3 amplifiers were used. The measuring signals were recorded on a 12-channel Honeywell Visicorder and reproduced on photographic paper. The vertical and horizontal force components for each foot were obtained for all steps taken on the walkway (Fig. 2). Walking speed was tested by measuring with a stop watch the time to walk between two marks. Calculation of gait cycle duration, stance and swing phase duration, step rate, stride length and maximal vertical and horizontal force amplitudes were made by hand. The vertical force impulse i.e. the area limited by the vertical force curve for each step was measured with a planimeter.

Additional equipment

(*a*) Photocells were placed 1.2 m above the floor on each side of the force plate walkway to get exact time measurements and triggering of the measuring procedure.

(*b*) Two more amplifiers were provided to make measurement of individual step lengths possible. The signal ratio of the two VFT of the same plate determines the position of the foot and therefore each signal has to go into its own amplifier and be recorded.

(*c*) The whole system was connected to a micro computer Luxor ABC 800. The data processing and calculations of the time–distance factors as well as the ground reaction forces and measurements of motion were performed by a specially designed computer program (Biomech. Lab. Munksjöskolan, Jönköping, Sweden) called "KI-Step" (Karolinska Institute). A plotter Hewlett

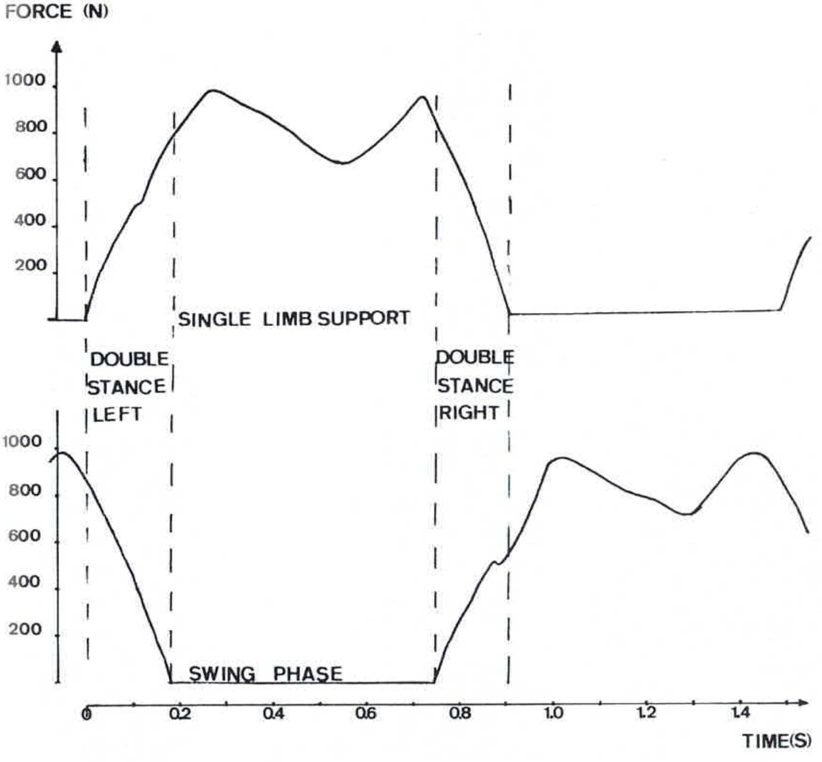


Fig. 2. Vertical force component curves for each leg recorded from the force plate walkway (detail).

Packard 7470 A was used for result presentation and a specially designed preprinted form as a protocol for each test.

Routine for calibration and testing
The routine for calibration is the key to the fast and efficient measuring technique. An 80 kg lead weight with wheels was made for this purpose. It can be placed anywhere along the force plates with immediate graphic presentation on the screen of the signals from each of the six force transducers.

Adjustments of mechanical problems
(*a*) *Analysis and filtering of the natural frequency.* Antonsson & Mann (2) found that 98% of the power is contained below 10 Hz and 99% below 15 Hz in normal walking with the highest frequency occurring at the foot during heel strike. This is in accordance with the findings of Rydell (11). Signals of normal walking from this force plate walkway had a frequency content of 6 Hz with the exception of 20–25 Hz sometimes seen on the horizontal curve. A frequency analysis of the electrical signals from the walkway was made after checking the rigidity of the construction. By generating a step load of 200 N and then analyzing the response the natural frequency of the system was found to lie between 45 and 50 Hz (Fig. 3). A third order low pass filter was mounted on the inputs of all six transducer amplifiers. It does not permit signals faster than 50 Hz to pass into the amplifiers and it eliminates most of the noise without destroying the force signal generated by walking. The delay of the measuring signal owing to the filter is 20±2 ms at the actual measuring range. It is important to point out, that this force plate walkway cannot record changes in forces that occur over 20 Hz due to its limited frequency range nor can it study the highest frequencies of gait i.e. initial foot contact.

(*b*) *Crosstalk and lateral moments.* Whenever several individual force transducers are combined in a mechanical structure crosstalk between the force signals is a problem. To minimize this the VFT were mounted more parallel to each other. A pure horizontal loading was more difficult to obtain. The crosstalk to the VFT was negligible when

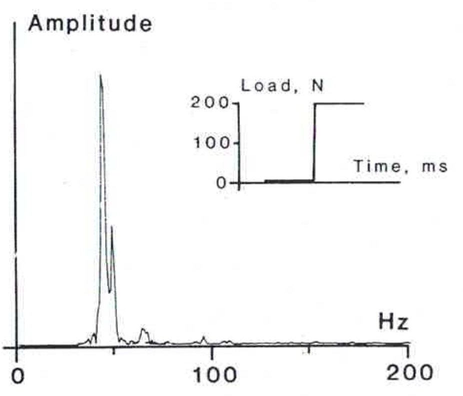
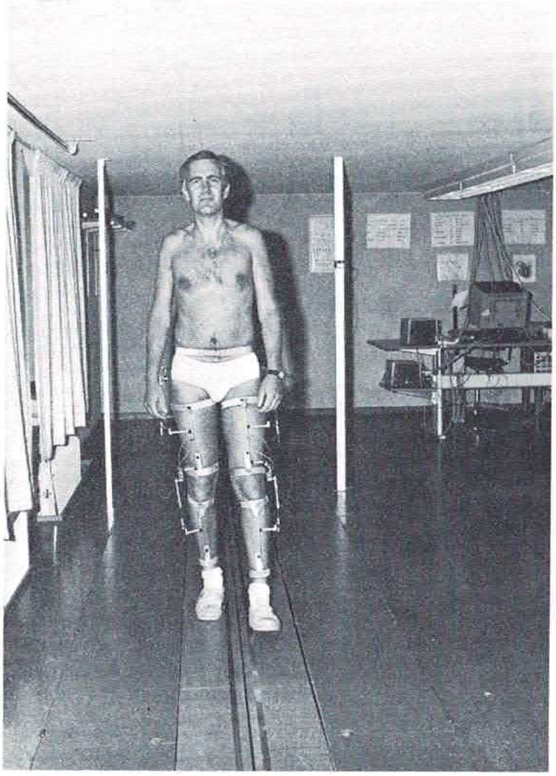


Fig. 3. Frequency spectrum from the system of a response to a step change in vertical force.



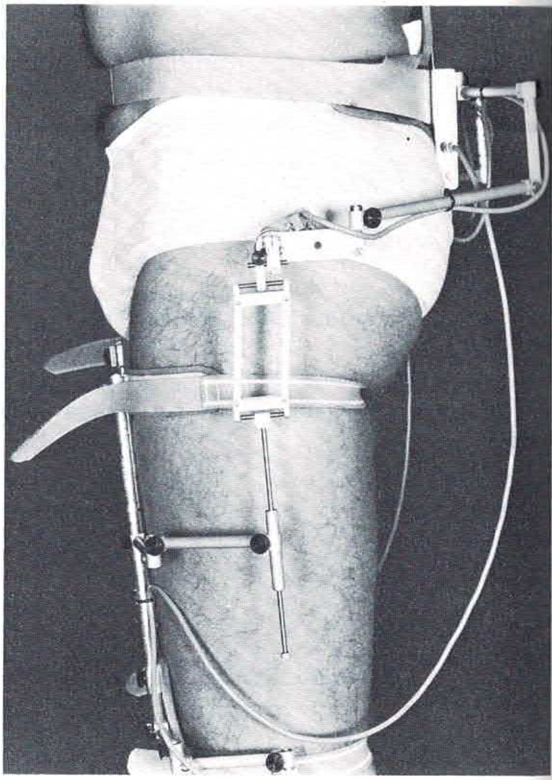


Fig. 4. (*a*) Electrogoniometer and walkway. (*b*) Close-up of electrogoniometer of hip joint.

using 10 kg weights, but for future development the HFT should be provided with links.

All six force transducers were sensitive to lateral moments, though steel rods with universal joints originally had been mounted to avoid this. They were all loosened to make the platforms "swing" back to their own unstrained position and after that secured in this position. To avoid sensitivity to lateral loading of the HFT, they were mounted more exactly opposite the middle of the short side of each platform.

Accuracy of force transducers

(*a*) *Stability*. The measuring error of stability was found to be less than 1% on the VFT but too great on the HFT to be satisfactory. For future development these should be preloaded in order to allow reliable measurement of the horizontal component of force.

(*b*) *Linearity*. Linearity was tested with eight different weights between 5 and 98 kg right above each VFT and 5 and 10 kg weights on the HFT. With this test method the deviation from linearity was less than 1%.

(*c*) *Hysteresis*. Hysteresis was tested with the same weights as above. The trials made indicate, that the walkway is accurate to within less than 1% in respect to hysteresis of the VFT. As mentioned above, registrations from HFT are not evaluated at the time being.

Reliability of step length measurements

(*a*) *Calculation of mean step length*. Two independent calibration methods were adopted. Subjects either stepped on an ink pad before walking on paper or stepped on marked points on the walkway with known distance in between. These step lengths were then compared with the mean step length, that was calculated by the computer as the ratio between velocity and step rate. The signals were simultaneously registered on a separate recorder during a gait analysis test. Furthermore the signals from foot switches were recorded separately during another gait test. These tests revealed systematic deviations between measured and indicated values. After having detected and eliminated some system errors, the discrepancy in step rate between the corrected data from the computer and the data from foot switch recordings and VFT was under 1%.

(*b*) *Calculation of individual step length*. In patients with lower extremity problems the individual step length may vary. This had previously not been measured by means of this walkway. Determinations of position were made using an 80 kg weight on ten different positions on each platform. The signals from each force transducer could immediately be seen on the display and the position was calculated according to the ratio of the two forces. When the transverse stability had been secured and the

Table I. *Variables analyzed by KI-Step*

Variable	Definition	Unit	Derivation	Method of validation
Body weight		Kg	Sum of four vertical force transducers (VFT)	Pair of scales
Average velocity		Cm/s	Photocells	Stop watch
Step rate	Rapidity with which steps are taken	Steps/s	VFT	Metronome, foot switch recordings
Mean step length		Cm	Velocity/step rate = step length	Foot switch recordings
Step length, right	Distance in direction of walking between left and right foot, when right foot is forward	Cm	The ratio of the two VFT of each plate determines position of foot. Mean value	Foot print measuring on floor paper and preset marks on walkway
Step length, left	When left foot is forward	Cm	The ratio of the two VFT of each plate determines position of foot. Mean value	Foot print measuring on floor paper and preset marks on walkway
Stride length/lower extremity length				
Stride length	Distance between successive points of foot to floor contact of same foot	Cm	2 × mean step length	
Lower extremity length		Cm	Functional lower extremity length is measured standing. From a place in the groin at the same level as the greater trochanter to the floor in front of the medial malleolus of the involved leg	
Gait cycle	Time interval between instants of foot-to-floor contact of same foot	s	Mean duration between two consecutive steps of the same foot. Recorded from VFT as 2/step rate	Foot switch recordings
Single stance phase, right	When only right foot is in contact with ground	% of GC	Mean duration of swing phase of opposite foot. Recorded from VFT	Foot switch recordings
Single stance phase, left	When only left foot is in contact with ground	% of GC	Mean duration of swing phase of opposite foot. Recorded from VFT	Foot switch recordings
Stance phase, right	When right foot is in contact with ground	% of GC	Mean duration of force signal recorded from VFT	Foot switch recordings
Stance phase, left	When left foot is in contact with ground	% of GC	Mean duration of force signal recorded from VFT	Foot switch recordings
Double stance phase, right	When both feet are in contact with ground and right foot is forward	% of GC	Mean duration of double stance when right foot is forward. Recorded from VFT	Foot switch recordings
Double stance phase, left	When left foot is forward	% of GC	Mean duration of double stance when left foot is forward. Recorded from VFT	Foot switch recordings
Time of single stance (involved/uninvolved leg)				
Maximal vertical force, right		% of BW	Mean peak force recorded from VFT	Kistler force plate recordings
Maximal vertical force, left		% of BW	Mean peak force recorded from VFT	Kistler force plate recordings
Weight bearing area (involved/uninvolved leg)			Integration of VFT-signal for each step	Planimeter recordings
Time from heel strike to maximal vertical force, right		% of SP	Calculation from the second complete stance phase	Kistler force plate recordings
Time from heel strike to maximal vertical force, left		% of SP	Calculation from the second complete stance phase	Kistler force plate recordings

GC= gait cycle, BW= body weight, SP= stance phase, VFT= vertical force transducer.

Table II. *Significant biomechanical gait variables*

Variables	Author	Available in this method
% Single support	Chao	Yes
Total sagittal motion	Chao	Yes
Stance flexion	Chao and Simon	Yes
Stance abduction–adduction	Chao	No
Stance axial rotation	Chao	No
Vertical force (% body weight)	Chao	Yes
T 2 (% stance)	Chao	No
T 3 (% stance)	Chao	Yes
% Weight acceptance time	Simon	Yes
External moments of the knee joint	Simon	No
Step rate	Simon	Yes

lateral moments no longer influenced the platforms, the measuring error was less than one centimeter.

Electrogoniometer

For measuring the angular excursions of the hip and knee joints in the sagittal plane a self aligning goniometer system is used. This was designed by Lamoreux (14) as a simplified version of his self aligning goniometer and manufactured by Machinator AB, Uppsala, Sweden. Four goniometers are mounted on a light weight aluminium exo-sceleton (Fig. 4). The system transmits the angles to be measured, while all other motions, that may result from misalignment between the position of the goniometer and the anatomic axes are absorbed. This arrangement allows the subject to walk freely. The potentiometers with a measuring error less than one degree within the measuring area are precalibrated. The reproducibility of the goniometer has been proved by Jansen and Ørbaek (8). The standard deviation of full measurement was approximately 5% of the hip excursion and 10% of the knee excursion.

Variables Recorded and Analyzed by KI-Step

Table I shows the gait variables, their abbreviation, definition, unit, derivation and the way they were validated. In every possible case the variable expresses the mean value of all complete steps recorded. A gait run with an obvious fault can be immediately eliminated. In order to record a full range of the variation in walking speeds each protocol admits twelve runs. One vertical and one horizontal force component curve for each foot from the last three runs of a subject are plotted on the protocol for confirmation of the data. The result is presented ten minutes after the gait is completed.

DISCUSSION

The accuracy of the method is related to calibrations. The VFT are calibrated with a mass of 80 kg ±0.5%. Including the resolution of the amplified and digitized signal from the transducer (0.1%) and the proper routines of calibration, the calibration error amounts to 0.5%. The total deviation from accuracy is thus of the 1% magnitude. This "unaccuracy" cannot be corrected, as it is a result of inherent deviations of the equipment and the means of calibration from the so called "true" values. In spite of the efforts to eliminate the sensitivity of the transducers to lateral moments, this remains a systematic error of force measurements during walking, if the subject consequently puts his foot on the lateral side of the force plate. Fortunately the loading during walking seems to occur in the majority of cases along a line just lateral to the middle of the force plate. Calibration should therefore be done with regard to this. Force measurement is indirectly included in the measurements of step length and duration of gait cycle, as these are triggered by certain points on the vertical force curve. The threshold value chosen in the program to decide position or start and end periods of timing may lead to a greater distribution in patients with pathologic walking. A statement of the total error is estimated at 2%, caused in a single measuring situation by variations in force measurement.

To the total error of 2% from the measurement of force the errors connected to time and distance measuring must be added. When calculating walking speed the time to pass the photocells on each side of the 5 m walkway is measured, during which registrations and measurements are made. Among occasional errors the way to pass the photocells should be noticed. A difference in position of breaking the beams of 10 cm i.e. forward and backward inclination respectively will give an error of around 1%. This error can be diminished by repeated measurements.

It should be pointed out, that the force plate walkway is not applicable to all types of gait disturbances. The subject must be able to walk unassisted by another person, walk with one foot on each plate, walk on both feet without a tow scuff along a straight line, avoid to put the walking aid on the force plates or the catches in the analysis program will give unreasonable values.

The maximum time for sampling information is limited to 10–12 seconds in the program, even though the last photocell has not been passed.

The errors of the different parameters accumulate according to chosen algorithms of calculation and the total error in a single measurement is estimated to maximum 5%.

In their separate works on gait evaluation of total knee replacement patients Chao (4) presented eight and Simon (12) four most significant biomechanical gait variables in providing discriminative power in separating normal and abnormal subjects. Of these twelve variables the authors have one in common. Of the remaining eleven variables seven are available in this method (Table II).

CONCLUSION

A previously described force plate walkway has been provided with additional equipment and computerized in order to give more accurate, efficient, fast and reliable information of the time–distance variables, movements in the sagittal plane and vertical ground reaction forces during gait. It can meet daily clinical need and be used as a clinical as well as a research tool. The long force plates provide a continuous record of a sequence of several steps taken by both feet, thus avoiding the problems connected with the usual small force plate.

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