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Software for analysis of equine ground reaction force data

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Software for analysis of force plate recordings of the horse at normal walk is described. The data of a number of stance phases are averaged to obtain a representative tracing of that horse. The amplitudes of a number of characteristic peaks in the force-time curves are used to compare left and right front limbs and left and right hind limbs. The averaged tracings are plotted, default on the line printer or, via a separate program, on a high quality pen plotter. A version of the program applicable for analysis of human force plate recordings, is available.

Force plate   Horse   Analysis of ground reaction forces

1. Introduction

Disorders of the locomotor apparatus in the horse are determined from a number of subjective criteria. Optimization of diagnosis, the study of the aetiology of lameness [1] and the evaluation of therapy [2] require a more objective analysis. The ground reaction forces evoked by the limbs during the stance phase can be recorded using a force plate. A number of investigators [2–8] have reported results from force plate measurements of horses. However, the results are difficult to interpret and compare due to the lack of standardization in experimental protocol and presentation of data.

This paper describes the hardware and software used in the Department of Anatomy and the Clinic for General and Large Animal Surgery of the Faculty of Veterinary Medicine, Utrecht University, for the quantification of the ground reaction force pattern from Dutch Warmblood Horses during normal walk.

2. Methods

2.1. Hardware

The Kistler force plate (type Z4852), size 0.6 × 0.9 m^2, is mounted on a heavy ferro-concrete construction in an outdoor track of 58 m length and 4.85 m width. The force plate and the surrounding area of 9.9 × 2.2 m^2 is covered with a 1.5 cm-thick rubber mat to prevent slipping of the hoof. The rubber mat also reduces the amplitude of the impact spike at the onset of the stance phase (Fig. 1). The charges evoked by the piezoelectric force transducers are fed via a 15 m-long cable (Kistler type 1681) to eight charge amplifiers (Kistler 5007). The two Q_x, two Q_y and four Q_z charges are summed in two Kistler type 5217 summation amplifiers, resulting in signals proportional to $\mathbf{F}_x$, $\mathbf{F}_y$ and $\mathbf{F}_z$. The Kistler dividing amplifiers (type 52151y12) calculate also the point of application of the resultant ground reaction force vector ($\mathbf{a}_x$

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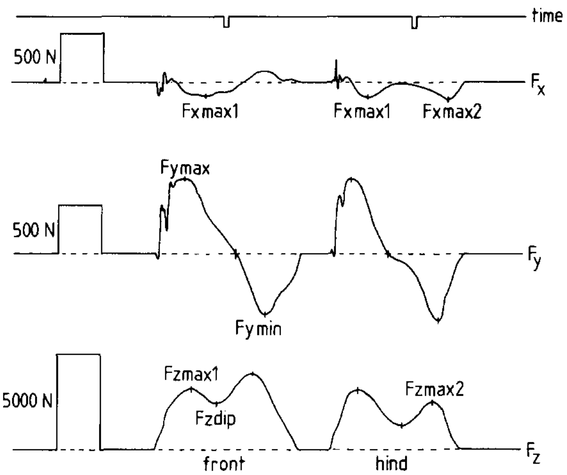

Fig. 1. Ground reaction force curves of a front and a hind limb stance phase of the horse at normal walk. $\mathbf{F}_x$ and $\mathbf{F}_y$ are the transverse and longitudinal horizontal and $\mathbf{F}_z$ the vertical ground reaction forces.

and $\mathbf{a}_y$) and the free moment around the z-axis ($\mathbf{M}'_z$).

Analog-to-digital conversion is carried out using a 16-channel 12-bit AD/DA convertor (type HDAS-16), connected to an Apple IIe microcomputer, consisting of a 6502 8-bits CPU, 128k RAM extension, two 5-inch diskette drives and a VDU. The sampling interval is software selectable and results from an interrupt generator of own design. The minimum achievable sampling interval is 160 μs per channel; in force plate measurements of the horse at normal walk six channels are converted using an interval of 10 ms. Data analysis is performed off-line on the CYBER 855 of the Academic Computer Centre Utrecht (ACCU), after transmission of the data via a 1200 bps line-driven permanent connection to the I/O-multiplexer.

The coordinate system to which the recorded forces are compared is defined so that the transverse (lateral) horizontal reaction force ($\mathbf{F}_x$) gives positive values during a reaction force to the right and negative values to the left, seen along the direction of walking of the animal. The longitudinal (forward–backward) horizontal reaction force ($\mathbf{F}_y$) gives positive values when the reaction force is opposite to the direction of walking and negative when the direction corresponds with that of walking. The vertical reaction forces ($\mathbf{F}_z$) are positive during the complete stance phase.

2.2. Experimental protocol

The animals walked at their own preferred, comfortable speed guided by an experienced assistant in a direction as parallel as possible with the y-axis of the force plate coordinate system. Data are collected from those runs in which both a front hoof and, after a short interval, the ipsilateral hind hoof are placed on the plate. At least five visually correct runs of either side are recorded. Runs containing information of the stance phases of either a front or a hind limb can be analyzed. However, these data are recorded only when the number of trials necessary for collection of sufficient complete runs is inacceptable regarding, for example, the lameness of the horse in study.

2.3. Software for data acquisition

The software was designed to meet a number of experimental circumstances encountered in our laboratory. After downloading the software from diskette, the first step is to initialize the converter software by selecting the number of channels to be converted and the sampling interval. Comments to be stored in the data file are entered via the keyboard. Thereafter, zero and calibration signals are fed into the converter. During data acquisition the input signals are displayed in real time on the VDU. After each run the content of the memory is either stored on diskette or discarded. The records of one data file are separated by an increasing extension number. The program is written in a menu structure so that persons who are not familiar with computer use can handle the system with minimal training.

2.4. Data file structure

The data file consists of a header of 9 lines containing filename, run counter, number of channels, number of data points in that particular run, sampling time, resolution, calibration data and units, and the line with the comment entered during initialization. The AD-converter output ranges from 0 to 4095, the zero input voltage corresponds with an output of 2048. The output values of the AD converter are stored in binary format on the diskette for reasons of optimal storage speed and storage capacity. Before off-line data transmission the binary-coded data are converted to three ASCII characters representing its hexadecimal value, to reduce the number of characters to be transmitted. The files are stored temporarily on 'permanent file' and, guided by the operator, on magnetic tape using ACCU facilities.

3. Software for force plate data analysis

3.1. Introduction

The software consists of three parts. First, the usable stance phases from the left and right limbs are selected from the original data. After averaging, an output file is written containing the averaged data of each of the four limbs and a number of selected parameters comparing left and right contralateral limbs. Line printer graphs of the averaged data can be produced. The second part produces graphs of the ground reaction force patterns of the horse under study, referred to the data of a 'standard horse' of similar breed and use. The third part is a program to create the 'standard horse' data by averaging the data from maximally 20 horses. All programs are written in FORTRAN77 (FTN5) for use on a CYBER 855 under NOS/BE operating system.

3.2. Averaging force plate data (program FRCPANX)

The program produces the averaged ground reaction force data of a number of stance phases of one limb obtained from a horse at normal walk, normalized to the duration of the stance phases and to the animal's body mass. This presentation allows comparison of different limbs of one horse and between horses. Analysis of data in trot is possible; only another subroutine for the analysis of the averaged ground reaction force parameters (see Section 3.2.6) must be loaded.

Input to the program is the data file as described in Section 2.4. It contains the sampled data of $\mathbf{F}_x$, $\mathbf{F}_y$, $\mathbf{F}_z$ $\mathbf{a}_x$, $\mathbf{a}_y$ and $\mathbf{M}'_z$ for all recored stance phases. Data at the beginning of each run correspond with the output signal of the unloaded force plate. It is followed by the stance phase signals of a front and a hind limb, and ends with no-loading data. The input to be supplied from the keyboard by the user of the program is a menu-switch that selects the requested outputs, identification of the horse (yy.mm.dd.nn + name), the animal's body mass, the number of stance phases recorded, limb side (either L(eft), R(ight) or W(rong)), switches to select or discard parts of a run and calibration values (i.e. 500 N/V) for each channel.

Using the $\mathbf{a}_x$ and $\mathbf{a}_y$ outputs of the force plate amplifiers (see Section 2.3), a hoof contact was marked with an asterisk as 'near the border' when the resultant ground reaction force was out of the square formed by the four force transducers supporting the force plate. Force amplitudes ($\mathbf{F}_x^2 + \mathbf{F}_y^2 + \mathbf{F}_z^2$) or stance phase durations deviating more than two times the standard deviation from the mean value were considered unacceptable.

The menu-switch input of the program is used to select output from the following possibilities:

(*a*) Onset, end, duration and amplitude of all hoof contacts.

(*b*) Averaged values of $\mathbf{F}_x$, $\mathbf{F}_y$ and $\mathbf{F}_z \pm 1$ SD at every 1/100 part of the stance phase of each of the four limbs.

(*c*) Comparison data of left and right contralateral limbs for a number of selected parameters useful for the characterization of the ground reaction force pattern.

(*d*) Line printer plots of $\mathbf{F}_x$, $\mathbf{F}_y$, $\mathbf{F}_z$ vs. time and $\mathbf{F}_x$–$\mathbf{F}_y$ and $\mathbf{F}_y$–$\mathbf{F}_z$ plots of the left and right front and hind limbs in one graph and a line printer plot of the $\mathbf{F}_y$–$\mathbf{F}_z$ curve of each of the four limbs in one graph.

(*e*) Result file on the disk containing parts b and c.

The flow through the program is illustrated in Fig. 2. The program structure is MAIN + 11 subroutines, executed consecutively. Some parts of the program will be discussed in more detail in the following sections.

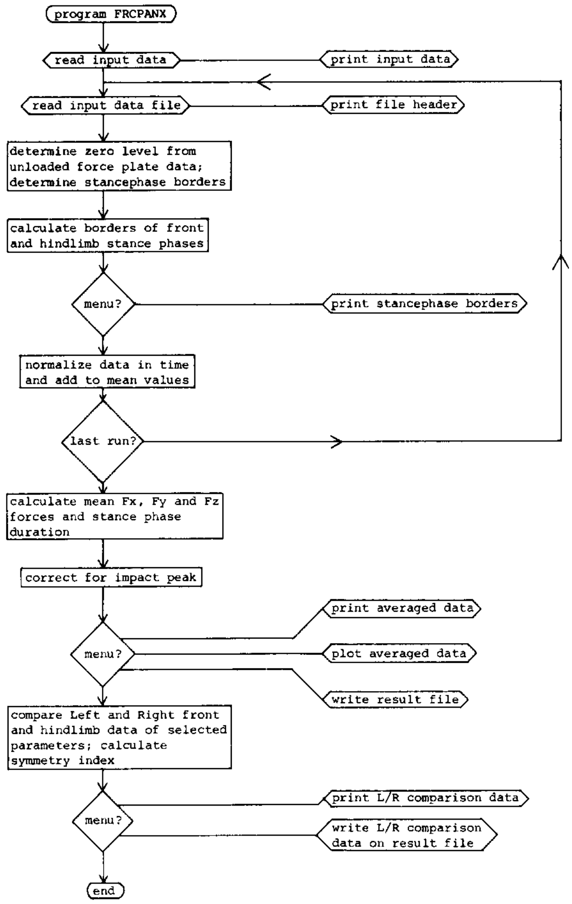

Fig. 2. Flow chart of the program FRCPANX for averaging and analysis of equine ground reaction force patterns.

3.2.1. Data read-in and data file (MAIN + RDFL)

The identification of R(ight) and L(eft) of the force data is not absolutely essential, since it can be deduced from the sign of the $\mathbf{F}_x$ force. However, this criterion holds only when normally walking horses are considered. It may lead to errors when data from lame horses are involved. Therefore, a check on R and L is performed on the basis of the $\mathbf{F}_x$ time integral (impulse). Whenever the sign of the $\mathbf{F}_x$ impulse does not correspond with the entered limb side, a warning message is generated. If a front limb or a hind limb stance phase is questionable regarding amplitude or duration, that stance phase data can be deleted selectively.

The subroutine RDFL for reading the data file is also used to convert the hexadecimal coded values to Newtons (forces), millimeter ($\mathbf{a}_x$ and $\mathbf{a}_y$) or N · m ($\mathbf{M}'_z$), using the zero and calibration values in the data file header. Error messages are generated if end-of-file is encountered or when the number of data points exceeds dimension bounds.

3.2.2. Determination of zero level (ZERDET)

The following procedure is carried out to correct for false force amplitudes due to drift of the apparatus. First, assume that AD signal conversion was started before loading of the force plate, i.e. the first data point approximates 'zero'. Correct all data in that run accordingly. Determine the maximum signal amplitude $(\mathbf{F}_x^2 + \mathbf{F}_y^2 + \mathbf{F}_z^2)$ during that run. Onset and end of the stance phase are defined to occur when the signal amplitude is less than 0.005 times the maximum. Check for being out of an impact peak at the beginning of the stance phase. Now the beginning and end of the stance phase having the larger amplitude are found. Usually, this will be the front limb, but in lameness it may be reversed. The following step is to deduce whether the determined stance phase borders are from a front or a hind limb. In the latter case, a signal peak must precede the previously determined one, otherwise, the hind limb peak must follow the former. All data points that are not included in the stance phase regions correspond with an unloaded force plate and are, thus, zero. The zero level is determined by averaging these data and the zero correction is performed.

If a run is incomplete, i.e. contains either front or hind limb signals or those from a limb improperly loading the force plate, the 'beginning and end of stance phase data' must be given in the input record. The zero determination starts then from the determined stance phase borders onwards.

3.2.3. Determination of stance phase borders (SDET)

The zero correction is performed in the previous subroutine. This influenced the amplitude of the signals and, via this, the determined beginning and end of the stance phase. Therefore, this determination is repeated on zero-corrected data values. In this routine the stance phases in which the resultant ground reaction force is located out of the center region of the force plate are marked.

These data must be checked carefully for correctness of amplitude. Guided by the menu-switch the stance phase borders, amplitudes and stance phase durations are printed.

3.2.4. Averaging data (MAIN)
Now that onset and end of the stance phases in the signals are known, the procedure of averaging can be performed easily. The duration of each stance phase is normalized to 100%; the amplitude of the signal at every percent stance phase duration is calculated by linear interpolation between the sampled data points. These values are added to those from preceding stance phases. As shown in the flow chart (Fig. 2) this procedure is repeated until all stance phases are handled. Then, the average force values are calculated by dividing the summed $\mathbf{F}_x$, $\mathbf{F}_y$ and $\mathbf{F}_z$ forces by the number of stance phases recorded.

3.2.5. Correction for impact peak (IMPACC)
A well-known phenomenon in force plate measurements is the impact peak occurring at the onset of the stance phase. The biomechanical significance of this peak is equivocal. Therefore, we eliminated this peak in the presented data. Starting from half the duration of the stance phase backwards, the tangent of the angle between the line from the onset of the stance phase to that data point signal is calculated. If the tangent of the current point deviates more than 20% from the previously determined value, the program assumes that a discontinuity in the force data, originating from impact, is found. The preceding data are then replaced by values obtained from linear interpolation between the onset of the stance phase and the first point after the impact peak. The interpolated points are marked in the averaged data file by changing their standard deviation values to -9.9999. Force data of each of the four limbs and the corresponding SD are printed at the request of the menu-switch in subroutine PRNT. This subroutine is also able to produce line printer plots of the averaged, impact spike-corrected force data.

3.2.6. Force plate data analysis (FRCAN)
Actually, this is the most important part of the program, since the parameters that characterize the force plate tracings are calculated here. The parameters that were found useful for this purpose are listed in Table 1. Obviously, numerous other choices can be made. As presented in another paper [9], these parameters were applicable to characterize the force plate tracing of the Dutch Warmblood Horse. Some parameters were combined to compare signals from left and right front limbs and from left and right hind limbs and resulted in the so-called amplitude symmetry index. On request of the menu-switch the determined characteristic force plate data values of all limbs are printed and written on the result file.

TABLE 1

Selected parameters from force plate tracings

	$\mathbf{F}_x$	$\mathbf{F}_y$	$\mathbf{F}_z$	$\mathbf{F}_y/\mathbf{F}_z$
Force	$\mathbf{F}_{xmax1}$ [a] $\mathbf{F}_{xmax2}$ [a]	$\mathbf{F}_{ymax}$ $\mathbf{F}_{ymin}$	$\mathbf{F}_{zmax1}$ $\mathbf{F}_{zdip}$ $\mathbf{F}_{zmax2}$	$\mathbf{F}_{ymax}/\mathbf{F}_z$ $\mathbf{F}_{ymin}/\mathbf{F}_z$
Time	peak $\mathbf{F}_{xmax1}$ [a] peak $\mathbf{F}_{xmax2}$ [a]	peak $\mathbf{F}_{ymax}$ peak $\mathbf{F}_{ymin}$ $t(\mathbf{F}_y = 0)$	peak $\mathbf{F}_{zmax1}$ peak $\mathbf{F}_{zdip}$ peak $\mathbf{F}_{zmax2}$	$\mathbf{F}_{ymax}/\mathbf{F}_z$ [b] $\mathbf{F}_{ymin}/\mathbf{F}_z$ [b]
Force *time [c]	$\mathbf{p}_x$	$\mathbf{p}_y$	$\mathbf{p}_z$	
Force *force				$\mathbf{F}_z d\mathbf{F}_y$

The ground reaction force parameters used to quantify the force patterns are indicated in Fig. 1.
[a] In hind limbs only; front limbs contain only one peak.
[b] The angle between the ground reaction force vector and the vertical is calculated in the yz-plane using $\mathbf{F}_{ymax}$ and $\mathbf{F}_{ymin}$, divided by the corresponding $\mathbf{F}_z$ value.
[c] $\mathbf{p}_x$ = transverse horizontal impulse during ground contact, calculated as the surface area below the averaged reaction force-normalized time curve, multiplied by the duration of the stance phase, similarly for $\mathbf{p}_y$ and $\mathbf{p}_z$.

3.3. Presentation of force plate tracings

When a force plate is used in the clinical setting, much attention must be paid to the presentation of the results to clinicians, who are usually not familiar with the 'normal' signal shape and the data acquisition process. On the other hand, the visual presentation of the tracings must be easy to interpret and, on the other, the tracings should be classified using figures that allow comparison between different horses. This philosophy requires the combination of three programs: (*a*) a program that produces high quality plots of the force plate signals; (*b*) a program that averages the force plate tracings from a number of selected horses, resulting in the tracing of a 'standard horse' and (*c*) a program that combines certain characteristic figures derived from force plate tracings into a 'limb-index', a 'symmetry-index' and a 'horse-index'. The latter program uses the force plate tracing of the 'standard horse' [9] and is described elsewhere [10].

3.3.1. Program to draw force–time and force–force graphs (PTINFP)

This program is used for the production of force–time and force–force graphs of one or more limbs in one frame (i.e. LF and RF, F_z) and graphs of a number of horses or recordings of one horse in one frame. All possibilities are menu-selectable. Due to this structure the program is easy to use, but the source text is difficult to read. The possibilities for graph selection are summarized in Table 2.

3.3.2. Program to calculate averaged force plate tracings of a number of horses (AVEFRC)

This program has been developed to create a 'standard horse' having force plate data that are found by averaging the data of a number of animals of the same use and breed. The program uses result files as described in Section 3.2 as input. The calculations do not need further description.

TABLE 2

Possibilities for graph selection in PTINFP

Menu	Print data of	Limb	Print data of
1	force $F_x(t)$	1	left front
2	force $F_y(t)$	2	right front
3	force $F_z(t)$	3	left hind
4	vector $F_x - F_y$	4	right hind
5	vector $F_y - F_z$	5	left + right front
6	menu 1 + 2 + 3	6	left + right hind
7	menu 1 + 2 + 3 + 4 + 5	7	limb 1 + 2 + 3 + 4
		8	limb 5 + 6
		9	all limbs in one graph

Menu = 6 means that graphs of F_x, F_y and F_z in three frames are drawn, similarly for menu = 7, limb = 7 and limb = 8. Menu and limb are variables in the plotting program.

4. Discussion

Although the larger part of the program FRCPANX is straightforward data analysis, there are some points that need further consideration. The averaging of force plate signals is open to discussion, although a number of arguments and research reports [11] support the view that averaged signals are more representative for the normal loading pattern than the signal from one single run. A well-trained clinically sound horse at normal walk demonstrates a remarkable reproducibility in walking velocity and shape of the force plate signals [9]. Furthermore, no correlation was found between signal amplitude, being merely determined by F_z, and the walking velocity and stance phase duration, all determined in the range where the animals walked at their own preferred, comfortable speed. For this reason it seemed reasonable to normalize the stance phase duration to 100% and average the obtained forces. Minor biological variation will always be present but this effect is now included in the averaged data and can be deduced from the standard deviation supplied in the print-out of the data.

The determination of the onset and the end of the stance phase is arbitrary. Especially the onset, where the impact peak frequently obscures the signal, is difficult to define. Input from kinematic analysis (i.e. high-speed film) is usually not as accurate as required for this purpose, unless very high frame rates are used and synchronity between both recordings is guaranteed. Foot switches or accelerometers may be applicable, but the necessity of instrumentation of the animals with long wiring or the use of telemetric equipment interferes with normal walk. Therefore, the position in time where the amplitude of the signal exceeds 0.005 times the maximum was considered to be a reasonable compromise. Obviously, the signal amplitude affects the calculated stance phase borders, but the slope of the curves is so steep, that this effect is usually negligible.

The occurrence of the impact peak is not understood completely. Since neither the amplitude nor the position in time of this peak is identical when comparing stance phases from one horse and comparing different horses, it must contain useful information. After coupling of high speed automated kinematic analysis apparatus to the force plate, we hope to be able to elucidate this aspect of the ground reaction force signal.

The program is written for analysis of force plate data from quadrupeds. However, a version of this program applicable for analysis of bipedal force plate recordings is also available. It is basically the same program with some adaptations in the parts for stance phase detection and the print-out and analysis of averaged ground reaction force data.

The tracings of the 'standard horse', being the averaged pattern of 20 selected Dutch Warmblood Horses, are very useful in those patients where no force plate recordings from former measurements are available. As shown in another paper [9], the resemblance between tracings of one horse over several years is greater than that between the horse under study and the 'standard horse'. Therefore, comparison with former tracings is preferred over the next best alternative, comparison with the 'standard horse'.

5. Availability

Copies of the programs can be made available at low costs.

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