A review and evaluation of available gait analysis technologies, and their potential for the measurement of impact transmission

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Abstract

The study of impact transmission is important for understanding how biological shock absorbers work and why they fail. However the study of impact in humans and animals poses several challenges, such as sampling rates greater than 1000 Hz and the movement of skin and markers affecting results. Since the 17th Century, gait analysis has been steadily progressing in complexity and accuracy, and this evolution has accelerated recently with the increase in computing power available. Optical systems are well-established but cannot achieve high enough sampling rates without controlled illumination, and have a limited capture volume. Inertial systems, combined with a wireless data logger, can increase the capture volume and achieve the required sampling rates. However factors such as accelerometer drift and the influence of magnetic fields are limitations. Force plates provide kinetic data for a single foot strike, with force shoes allowing continuous data at the expense of accuracy. Medical imaging and electromyographic systems often accompany gait analysis for measuring morphology and muscle activation, to facilitate computational modelling of the musculo-skeletal system. Feasibility tests have shown that some of the challenges of the study of impact can be addressed by each technique but to solve them all will require a hybrid system making use of several technologies.

1. Introduction

Shock absorption deals with the dissipation of the forces generated during impact. Impact force can be defined as a force resulting from the contact of two objects that reaches its maximum less than 50 milliseconds after the initial contact [3-5]. Figure 1 shows an example of an impact force on a force-time graph of the vertical ground reaction forces generated during human walking. The purpose of a shock absorption system is the protection of the system or body to which it is attached. All mechanical and biological shock absorbers have limitations and exceeding these can lead to damage of the systems they are protecting [5]. In order to find the limitations of biological systems it is necessary to know how the impact force is transmitted, and this will allow the prediction of the conditions under which a system will be damaged or suffer catastrophic failure [6]. Ensuring the system is not subject to these conditions is an important consideration in fields such as the design of sporting venues and surfaces [7].

Mechanical shock absorbers work using a combination of springs and dashpots in order to absorb the force of the impact and to damp vibrations. In biological systems this dissipation is accomplished by a combination of joints, muscles and tendons [8, 9]. The study of biological shock absorption is of interest because the process of refinement has constantly improved and optimized each species' system to accomplish its task. In some species it is also thought that the energy absorbed by the system during impact is stored as elastic potential energy in the tendons and then re-used for locomotion when the system is unloaded [9, 10].

The aims of this PhD are to investigate the damping of the impact forces generated during cursorial locomotion and how each part of the limb functions in this capacity. Cursorial locomotion is defined as high speed over ground locomotion [8] and impact transmission systems used in this motion allow the animal to run over several different types of terrain. There will also be a focus on how anatomical variations between species [8] affect their impact transmission and look at this alongside the species environment to determine if there is a link. The hypothesis is that each species operates near to its safety threshold for its expected loading. Finally the research will expand to look at impact transmission in humans and the effect of deterioration in the human shock absorption system. The focus of this paper is a review of the gait analysis technologies available and the challenges posed in the study of impact transmission.

The study of impact transmission requires the collection of kinematic and kinetic variables that describe locomotion, and can be two-dimensional or three-dimensional. Kinematic data describes the motion of a system and looks at a subject's gait without consideration given to its mass or the forces acting upon it [3]. Kinematic data collection usually gives the coordinates of markers or points being tracked [11]. This data can be applied to a biomechanical model in order to analyse the movement of the subject. Kinetic data describes the forces that produce or result from movement [3]. A force plate is used to measure ground reaction forces [1, 11]. This can be combined with kinematic data and inverse dynamic modelling is used to work out parameters such as the net moment about each joint, muscle forces and joint contact forces [12].

2. A Brief History of Gait Analysis Techniques

Whilst the ideas and techniques for gait analysis have been around since the latter part of the 17th Century it is only in the last 150 years that these have been put into practical use and equipment developed with this use in mind [3]. From the initial work of Marey [13] and Muybridge [14] in the late 1800s, development has progressed beyond research-based work and in the late 1960s the first commercial system became available. This was a piezoelectric force plate, developed by Kistler (Kistler Group, Switzerland) for use in a laboratory [3]. Accelerometers began being used in the mid-1970s [15] and the 1980s saw the Oxford Orthopaedic Engineering Centre produce the Vicon motion capture system (Vicon Ltd, U.K.) [3]. With the rapid advances in computing power that came in the 1990s gait analysis techniques have advanced significantly. Motion capture cameras and force plates are now well established technologies [1, 11, 12, 16], with accelerometers, inertial systems and other techniques also in use [17-19].

3. Current Technologies

3.1 Video Cameras

The use of video recording for gait analysis can be performed with or without markers on the subject. Two-dimensional analysis requires only one camera positioned perpendicular to the plane of movement of interest, but the results can be affected by out-of-plane motion [1]. Three-dimensional analysis looks at movement in all planes of motion and requires more than one camera [12]. The points of interest on the subject must be visible by at least 2 cameras at all times in order to reconstruct their positions [3, 11]. Data sampling rates for optoelectronic systems vary from 50-1000 Hz [3, 20]. A sampling rate of 60 Hz is adequate for equine kinematic analysis at walking speed [1] but shock absorption is more pronounced at faster locomotion as the impact forces will increase. To increase the sampling rate the shutter speed of the camera is increased and the shutter will be open for a shorter time leading to a decrease in the amount of light reaching the cameras sensor. The aperture of the camera is then increased to maintain this light level. As the shutter speed increases the aperture may be unable to compensate for the decrease in lighting level and so artificial lighting may be required [21]. The viewing angle and focal distance of the cameras places limits on the size of the capture volume in which motion must take place [3]. If markers are used, skin movement artefacts [22-24] caused by the skin moving over the musculo-skeletal structure must be removed from the data before reconstruction of movement can be performed.

3.2 Optoelectronic Systems

Optoelectronic systems convert light signals into electrical signals and track the light emitted or reflected by markers. Active markers emit a signal and come in the form of small LEDs that can be attached to the subject [1]. Passive markers reflect light emitted by the cameras back to them [1] and near infra-red light is used to illuminate the markers. Data sampling rates for optoelectronic systems vary from 50-1000 Hz [3, 20]. The work of Linford [20] has shown that for for the analysis of equine joint angular? motion at the trot increasing the sampling rate from 60 to 1000 Hz does not increase accuracy significantly. Figure 2 shows the layout of 6 optoelectronic cameras used to capture human or animal locomotion. The skin movement artefact will still be present [22-24] as is the limitation of having a finite capture volume in which motion must occur [3].

3.3 Electromyography

Electromyography (EMG) is used to detect and measure the small electric current produced by muscles during contraction [1]. Sensors can be placed on the skin or fine wires inserted into the muscle of interest [1, 25]. A feasibility test was done to examine the signal strength of the equine *vastus lateralis* muscle, used in locomotion, when recorded through using skin-level sensors through an unclipped coat. The time at which the muscle became active was clearly distinguishable (Figure 3). Data on muscle activity/inactivity is used when looking at what muscles are involved in a motion. Placing the sensors on the skin can give erroneous readings for a specific muscle as other muscles lying around or on top can cause cross-talk in the signal [25]. Inserting electrodes into the muscle itself gives more accurate readings for the muscle activation [25].

3.4 Force Plates and Force Shoes

A force plate consists of a steel plate with transducers at each corner. When a load is applied to the plate it is detected by the transducers. This is then converted into an electrical signal. The magnitude and direction of the force is measured and the instantaneous centre of pressure can be calculated [3]. The size of force plate used and the range of readings it can measure are chosen to suit the application. Figure 4 shows the Kistler 9287B Large Multicomponent Force Plate for Biomechanics (Kistler Group, Switzerland) own by Newcastle University and includes the axes convention used for the measurements recorded. It has a range of ±10KN in the x- and y-axes, and -10 KN to +20 KN in the z-axis and has been used in the study of equine locomotion. The 9287B force plate has a contact surface area of $0.54m^2$ on which the subjects foot/hoof must make contact during the motion being looked at. In the past force transducers have been used to create an instrument treadmill [1, 16] and this means there is no longer a limit on the number of steps captured. It is important to know the expected range of readings for the motion being analysed in order to select an appropriate force plate.

Force shoes typically consist of piezoelectric load cells mounted between two metal plates [2, 26]. A load cell contains a quartz crystal which will generate an electric charge when a mechanical strain is applied [3]. Each load cell is mounted on the metal plates using a screw passing through its centre [2, 26]. The upper metal plate is then affixed to the subject and the wires from the load cells secured [2]. Figure 5 shows the force shoe described by Chateau and colleagues [2] for use on horses. Previous work has used data sampling rates of 4100 and 8000 Hz [2, 26]. The combination of the load cells and metal plates gives force shoes a thickness of around 10 mm [2]. Compensator blocks are affixed to the subject's opposite limb in order to negate any effect the addition to its limb length has upon its motion [2]. The mass of a force shoe used in equine gait analysis can vary from 490-700g [2, 26] and the compensator on the opposite limb has the same mass as the force shoe. The screws passing through the centre of the loads cells transmit some of the force applied directly to the upper metal plate and so the ground reaction force (GRF) measured can be up to 15% less when directly compared with the GRF measured by a force plate [26]. Shear forces can occur between the layers of the force shoes during locomotion causing further inaccuracies.

3.5 Inertial Systems

Inertial systems are composed of accelerometers and gyroscopes which work on the principle of measurement of inertia, the tendency of an object to resist a change in motion. Accelerometers operate on a "spring-mass" principle. Two charged plates are separated and the capacitance/resistance between them is a function of their separation. One plate is suspended over the other on flexible mounting and acceleration causes this mounting to flex giving a change in plate separation [3]. The change in capacitance/resistance is measured and the change in separation calculated. The second derivative of the change in separation with respect to time gives the acceleration at the attachment point. In previous biomechanical studies data sampling rates of 100-10,000 Hz have been used [4, 5, 7, 18, 27]. Accelerometers can detect accelerations up to 10,000 g [3] and the data collected by tri-axial accelerometers give the sensors' acceleration in three dimensions. Skin movement artefacts can affect the readings of accelerometers [22-24] and must be compensated for. The movement of the skin itself will cause acceleration, as will vibration of the sensors after the subject makes contact with the ground.

Gyroscopes are devices used for measuring orientation and can be used in gait analysis to give segment orientation [28]. In order to obtain the limb orientation the angular acceleration must be integrated twice with respect to time and this will amplify any initial errors. The sampling rates used for gyroscopes are similar to that used in accelerometers [18]. The sensors themselves are small and lightweight, and can detect a large range of angular velocities [3]. Gyroscope readings are subject to drift caused by changes in the direction of motion [29]. If gyroscopes are combined with accelerometers then the data can be used to obtain the kinematics of the subject's movement [18]

3.6 Other Technologies

An electrogoniometer consists of a potentiometer with two rotating arms [1]. The centre of rotation of these two arms is placed over the joint centre with the arms then attached to the adjoining segments. As the joint moves this changes the resistance of the potentiometer and the joint angle change can be found from this. Figure 6 shows an electrogoniometer attached to an equine leg. The joint angles are measured in one plane and the system requires accurate calibration of the potentiometer [1]. Electrogoniometers take time to attach to a subject as the potentiometer arms have to be secured attached to the limb segments and the centre of rotation precisely over the joint [30], and so are inappropriate if time is an important factor. Research carried out on joint angles using electrogoniometers has shown them to give reliable results for joint movement in the human hand [31] but when compared directly with a Vicon system looking at knee movement it was shown that the two cannot be used interchangeably to measurement knee joint angle [32].

Magnetic systems generate a magnetic field and use this to track ferromagnetic markers that cause distortions within this field [33, 34]. This technique does not require a line of sight for the markers. The metal content of the area in which the magnetic field is generated must be considered otherwise this will distort the field just as the markers do [33]. The metal content of the earth itself will also distort the field. Magnetic field sensors can also provide a reference axis for calibration of gyroscopes using the magnetic field vector [19].

Medical imaging systems have two functions in gait analysis. Magnetic resonance imaging (MRI), computer tomography (CT) and ultrasound are used to obtain geometric/anatomical data of a subject's limb [3]. This is then used to customise a computational model of the subject to which kinematic and kinetic data can be applied [3]. MRI and CT have also been used to evaluate static positioning of limbs [35] and the movement of limbs [36, 37].

4. Challenges Posed in Studying Impact Transmission

The study of impact transmission will involve applying the data collected on impact force and transmission for a subject to a computational model of the subject's limb. This will be used to analyse the movement of the limb during the impact. There are some challenges posed in the collection of the data for use modeling.

4.1 Measurement of impact force and shock absorption

Impact force has been defined as a force resulting from the contact of two objects that reaches its maximum less than 50 milliseconds after the initial contact [3-5]. This short time scale over which the impact force will be measured implies a sampling rate for recording data will be required that is sufficient to ensure under-sampling does not occur. Previous research using accelerometers to measure the acceleration experienced at impact in various species [5, 18, 27] has used sampling rates of 10,000 Hz. Force shoes and plates using sampling rates of 8000 Hz have been used to measurement the ground reaction force in equine subjects at trot [2] and the results show the impact force at the start of the loading cycle. Measurement of the impact transmitted by the subject's limb proximal from the point of contact will not require these high sampling rates. The results from Henriksen et al. [38] measured the acceleration at the trunk due to impact from human walking, with the data sampled at 250 Hz. As shock absorption occurs, the acceleration measured by the sensors placed on a subject will decrease as you move proximally. This damping will decrease the magnitude of the impact and its frequency.

4.2 Marker attachment

If markers are used, the forces experienced at impact make secure attachment necessary and the method chosen must minimise the vibration of the markers. Markers can be attached to a subject using Velcro, medical tape, wrapping bandages, plastic plates, elastic straps and bone pins [39, 40]. Double-sided medical tape is attached to the subject and the markers then fixed to the tape [39]. Feasibility studies with horses have shown that even if a good attachment is made using this method, the markers can still be dislodged by the impact of the subject's hoof on the ground and this will increase with the speed of locomotion. Wrapping bandages can use either an over-wrapping approach where the bandages pass over the base of the marker, or an under-wrapping approach where the markers are attached to the bandage. It has been shown that an under-wrapping approach gives the best results [39]. Wrapping bandages can be used to attach either individual markers or plastic plates. Plastic plates have several markers attached to them and are held in place by medical tape or wrapping bandages [39]. Markers can also be attached to elastic straps and Velcro [41] but the contraction and relaxation of the muscle underneath the straps can cause their positions to change during locomotion. Marker-free tracking can resolve the issue of marker attachment.

4.3 Skin movement artefact

Skin movement artefacts are caused by the skin moving over the musculo-skeletal structure [22-24]. The movement of any markers on the skin may not exactly match the movement of the subject's skeleton [42, 43]. Therefore the skin movement artefact should be removed before the movement data can be used in modelling the subject's motion. One technique available is to use bones pins [22, 23, 44]. This involves embedding metal pins into the subject's bones at points of interest and then attaching markers or sensors to the pins at skin level [44]. A technique which reduces the invasive aspect of the previous method is to use a single bone pin inserted at an anatomical land mark [45]. The movement of markers at other points are assessed relative to this and the affect of the skin movement on the markers can be calculated. A non-invasive technique applies an algorithm to the movement data during processing and removes the skin movement from it at this stage [24, 46, 47]. This method has been shown to remove most of the skin movement from data and with the remaining error forming a confidence band for the results [47]. As this research into impact transmission intends to use the least invasive methods possible, the processing of the data using skin movement algorithms would be preferable.

5. Conclusions and Future Work

There are several techniques available for gait analysis and some challenges to be overcome in the study of impact transmission, such as the skin movement artefact, marker attachment and impact force measurement. Previous work has shown solutions for each of these problems [2, 39, 47]. Work in the near future will focus on the selection of one or more gait analysis techniques that will provide sufficient data to enable the study of shock absorption systems and impact transmission in both humans and animals. To accomplish this, further feasibility studies will be carried out to look at what effect the limitations of each technique has on this field of study.

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Figures and Tables

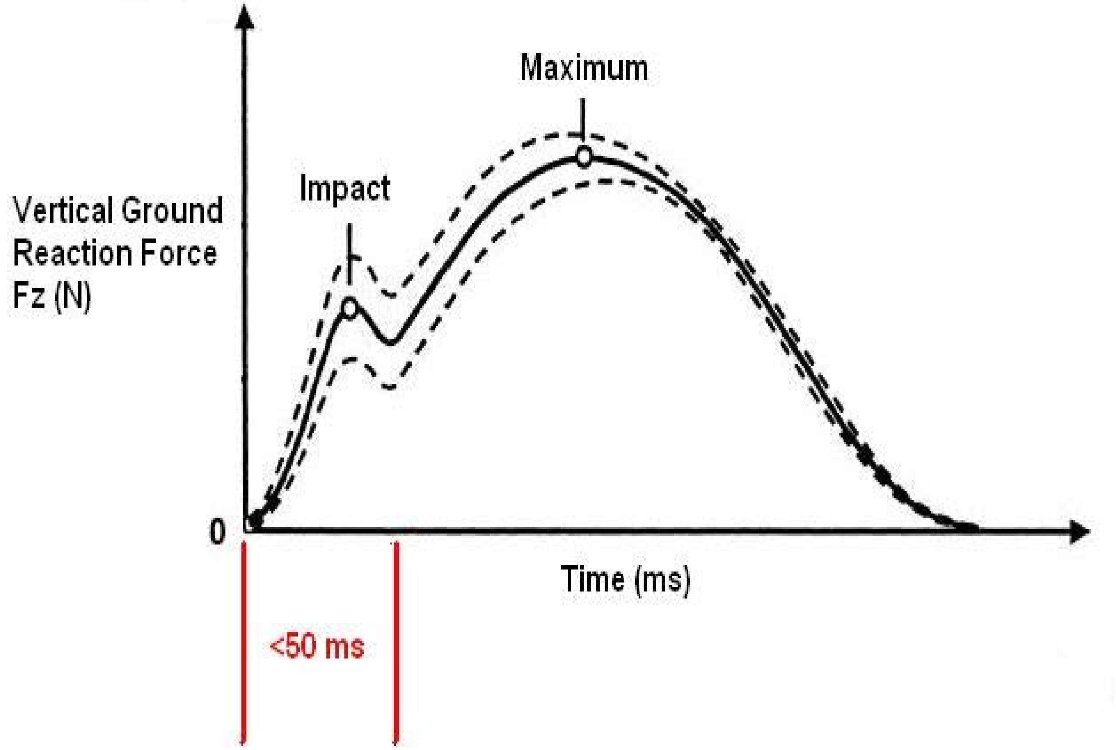

Figure 1. Graph to show impact force in relation to loading history for ground reaction force generated during walking.

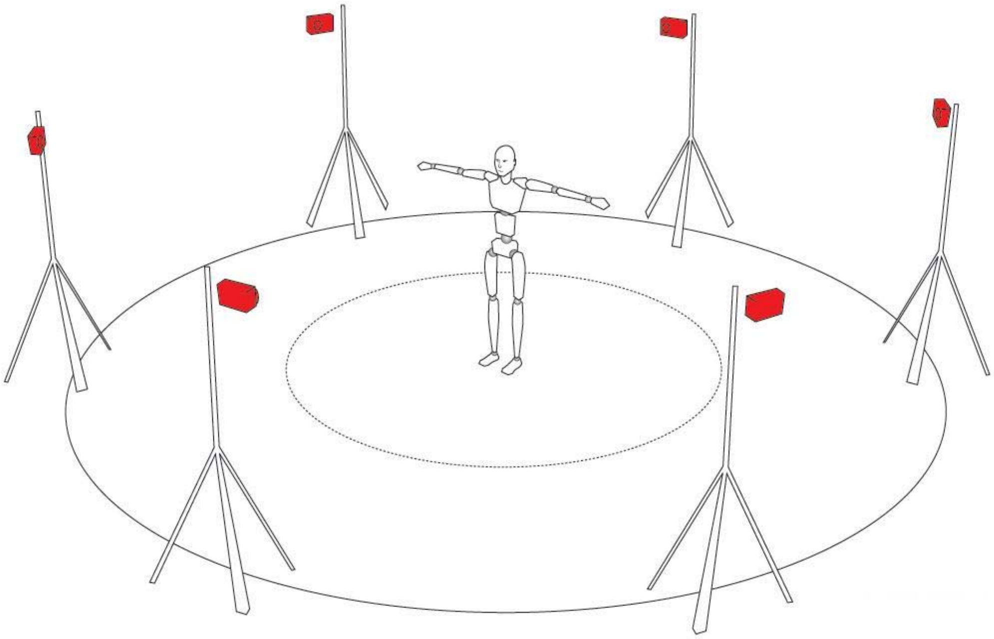

Figure 2. Positioning of motion capture cameras during human gait analysis.

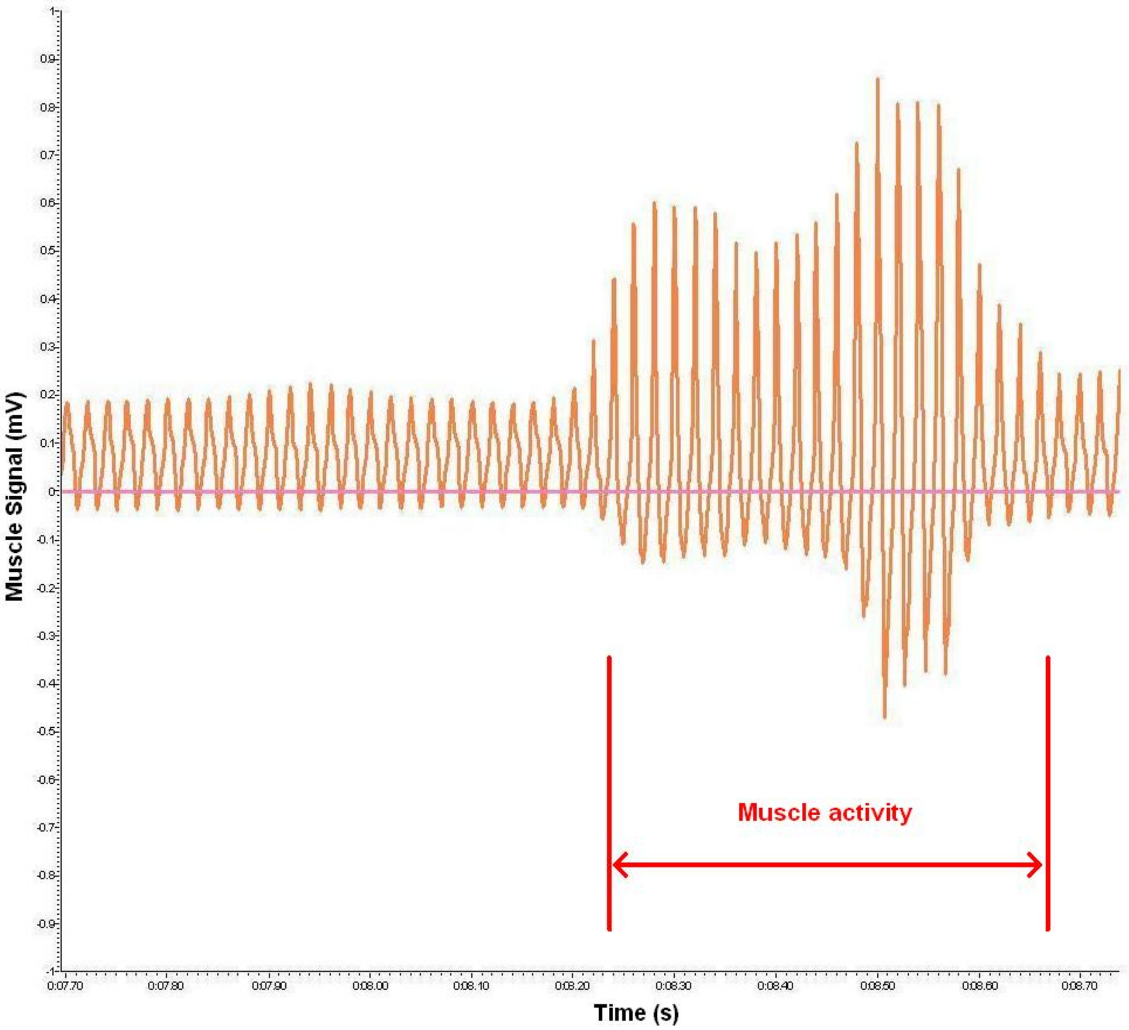

Figure 3. Typical graph of muscle signal from the equine *vastus lateralis* muscle recorded during feasibility study using skin level sensors on an unclipped horse at walk.

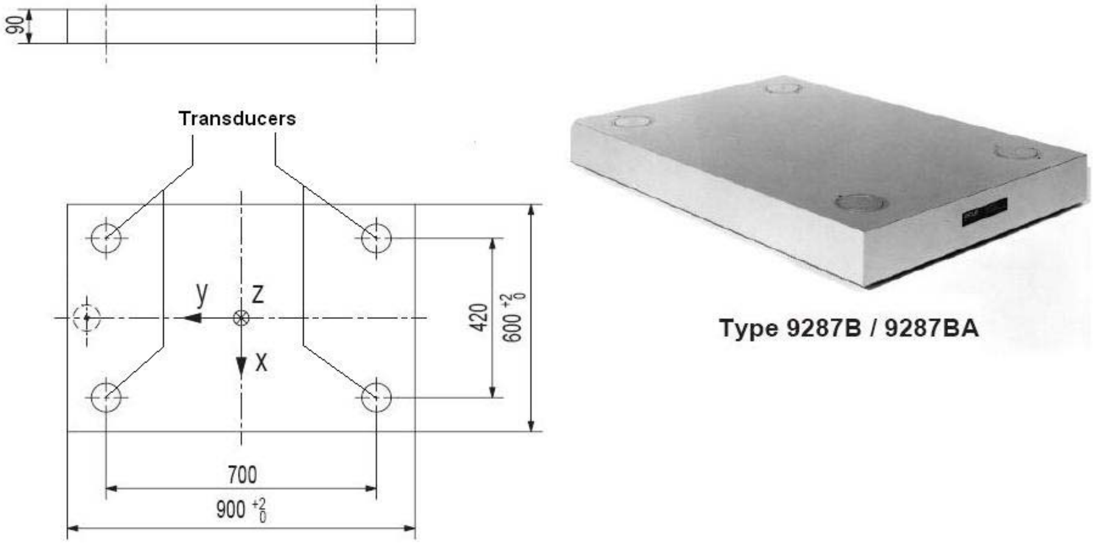

Figure 4. Typical transducer layout used in a force plate, illustrated using Kistler 9287B Force Plate (Kistler Group, Switzerland)

Figure 5. A force shoe described by Chateau et al. for use with horses [2].

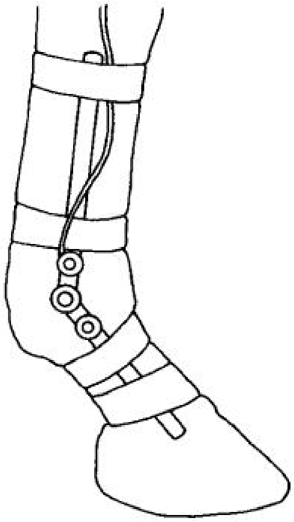

Figure 6. An electrogoniometer attached to the equine fetlock joint [1].