THE BIOMECHANICAL DETERMINANTS OF POST-FLIGHT PERFORMANCE IN SIDE-HORSE VAULTING.

by

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ABSTRACT

In an attempt to determine the interaction of the three phases of a vault with a view to predicting post-flight performance from properties of pre-flight and contact behaviour, six highly-skilled subjects were filmed and their contact forces simultaneously monitored while performing the layout squat, handspring and Yamashita vaults. To provide an objective criterion of performance a rating for each vault was derived, based on height and distance of the post-flight of the vaults.

The cinematographic data was subsequently digitised using a Vanguard analyser linked to a Minc mini-computer and eleven co-ordinates specifying the position of nine major body segments in each frame were read into the file. This file was transferred off-line to the Prime system and the centres of gravity of each subject determined using the segmental method. The resulting displacement-time data was smoothed to reduce the usual random measurement variations. A least-squares polynomial, of degree one, was adopted for use with the constant velocity horizontal data and a cubic spline for the changing velocity vertical data. The horizontal and vertical velocities were calculated from the smoothed values. Angular velocity and displacements of the body during pre-flight were also determined.

The force traces were recorded from two biomechanical force platforms during horse contact. These traces were integrated to give horizontal and vertical impulses. Average forces were calculated. The kinetic and kinematic data thus obtained were combined to specify the mechanical characteristics of the pre-flight, contact and post-flight phases of the vaults.

The paths of the centres of gravity in post-flight were observed to be related to specific pre-flight characteristics. The predictive equations developed confirmed these observations and showed that for all vaults vertical velocity at horse contact was an important variable. Post-flight was found to be dependent upon pre-flight for the three vaults.

The equations were evaluated on results derived from cinematographic data for three different subjects performing one of the vaults each, and on one subject from the original group who performed the layout squat and handspring vaults with experimental modifications of her pre-flight. The equations were found to be valid for the handspring and Yamashita vaults. The results for the layout squat vault indicate that the equation was too specific to be applicable outside the ranges shown for the independent variables. However the principles of high vertical velocity at contact and short duration of pre-flight which govern performance were still found to be valid.

The vaults were ranked according to their angular momentum requirements in post-flight. The handspring front vault was also included in this analysis. It was found that angular momentum in post-flight was a function of angular velocity in pre-flight to a limit where pre-flight angular velocity does not increase. At this point vertical velocity at horse contact becomes more effective and the duration of post-flight is increased.

It is concluded that the optimum characteristics of performance in the early phases of a vault are specific to each vault. As these characteristics determine post-flight performance more attention should be paid to their precise execution by gymnasts and coaches than has been previously recommended.

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CHAPTER 1

INTRODUCTION

CHAPTER 1: INTRODUCTION.

BACKGROUND TO THE PROBLEM

In 1962 Yamashita first performed, at an international level, the modification of the handspring vault to which he has since given his name (Taylor, Bajin and Zivic, 1972). By the early 1970's double twisting Yamashitas were in vogue and Tsukahara introduced his 'new' vault to the gymnastic world (Fink, 1974). These events have brought about a dramatic change in the style of vaulting, the emphasis since being placed on the post-flight and the execution in it of complex somersaults and twists. To achieve such dominance in the post-flight it is essential to achieve both maximum height and great angular momentum. Prior to this time the pre-flight phase was considered to be of particular significance and this led to the widespread use of the through vault in which the layout squat vault commonly featured. These vaults are in direct contrast with the handspring vaults in that the direction of the body's rotation changes upon contact with the horse to bring the feet underneath the body during post-flight. Their popularity however waned, and they were replaced by the handspring vaults where the rotation initiated at take-off continues in the same direction throughout the vault. Handspring vaults existed in other forms before this Japanese inspired revolution, but these lacked all the lift and élan of the modern vaults. The handspring vault described by Ferriter (1964) would today, at best, be considered as a handspring drop vault: it lacks height and range in post-flight.

The style of vaulting is largely governed by the Code of Points and, for women, these have changed recently (International Gymnastics Federation (I.G.F.) Code of Points, 1979) to allow for the development of the new style, reducing the emphasis on the 1:1 symmetry between pre- and post-flights. This change gives rise to the question of how does this shift in the emphasis of vaulting affect the future of the sport i.e. what skills will be allowed to blossom in the new freedom? Some ideas may be gained be analysing the mechanics of the vaults, others will be created by inspired coaches and daring gymnasts. The natural laws governing the movements of the body may reasonably be explored first to see what insights they provide, for instance to uncover answers to such questions as: Does a low trajectory in pre-flight mean that the post-flight will necessarily be higher? Even such fundamental questions appear to remain largely unanswered (Dainis, 1979; Hatano, 1976; Hendershott, 1974).

Fukushima (1974) compared the pre-flight of his good subject, Kato, with that of a less proficient gymnast,

> Kato's path, especially that of his upper body, was close to a linear pattern rather than T's normal trajectory path. T's whole body flew in an arc, however Kato's arms, head and shoulders were kept about the same height and only the lower part of his body showed a curved path; as if he held his head and shoulders and turned only his toes. (p.15)

Apparently Kato had a lower pre-flight trajectory than T, whose body flew in an arc, yet the description of Kato's flightpath is more concerned with the rotation of the body than with the path of the centre of gravity itself. While both of these factors are important, a clear distinction needs to be made between them.

Disagreement exists as to what is a low pre-flight. Some authors refer to it as a low trajectory (Fukushima, 1974), others as a low angle between the vaulter and the horizontal during contact with the horse (Bajin, 1976b; Fink, 1974). George (1980) suggests that the handspring vault needs a low, flat pre-flight in order to realise maximum amplitude in the post-flight trajectory. The handspring front, he suggests, needs an even flatter and shorter pre-flight than the handspring vault, but still requires a high body angle on contact with the horse. The need to obtain high angular momentum in the handspring front is obvious and one way to achieve this may be to shorten the pre-flight. However, what effect will a lower, shorter pre-flight have on the path of the centre of gravity during post-flight? Is there an optimum pre-flight for each type of vault? The answer is not apparent.

The layout squat vault requires a contact angle well above the horizontal. Formerly this was accomplished with a high pre-flight, it may be that this high pre-flight was unnecessary, for lowering the pre-flight in this vault could, perhaps, lead to an adequate enough increase in the post-flight trajectory to accomodate the vault. However, George (1980) recommends that the pre-flight in this vault be higher than those for the handspring vaults. Hendershott (1974) suggests that the layout squat vault is better performed with a speedy pre-flight, which implies a low trajectory. If the high body contact angle is to be retained, then this low trajectory implies a greater angular momentum in the pre-flight which has to be reversed during contact with the horse. In this situation the questions arise whether or not the gymnast could affect the angular momentum changes enough while in contact with the horse to complete the vault successfully and by how much would any increase in the time of the post-flight help in decreasing the amount of angular momentum change otherwise necessary? Dainis (1979) has published quantitative data for the handspring vault. He found that the vertical velocity of the centre of gravity at horse contact was the most important factor in determining the outcome of the vault. The vaults were awarded kinematic scores on many variables during both pre- and post-flights and these were then correlated with the pre-flight variables. He found that the worst vaulters had a downward velocity upon contact with the horse i.e. a high pre-flight, and that the best vaulters were still moving upward when they made contact.

This work forms the basis from which this study is attempted. Dainis used the initial phases of the vault, until initial contact with the horse, in his correlation with the score. He did not take the forces evoked during contact into account, and therefore could not see the interrelationship between pre-flight, and the forces on contact induced by the pre-flight.

It is the intention of this study to quantify the forces evoked by the gymnast in the support phase of the vault which change the path of the centre of gravity and the angular momentum in post-flight, and to see how pre-flight behaviour assists in this task.

Predictive models will be developed, based on pre-flight and support force parameters, and applied to vaults of different properties, classified by post-flight complexity, to reveal the importance and interrelatedness of the different phases of the vault.

The purpose of this study may be stated as follows:-

The purpose of this study is to show how the biodynamic characteristics of the initial phases of gymnastic vaults determine their post-flight.

In order to achieve this purpose a series of questions require answers. When satisfactory answers to these questions have been given then the purpose of this study will have been achieved.

1) What are the biodynamic characteristics of the pre-flight, contact and post-flight phases of the vault?

2) Which of the biodynamic characteristics of the pre-flight are most instrumental in producing the best post-flight?

3) In what way are the performance variables of contact due to the pre-flight and to what extent do they account for post-flight behaviour?

4) If pre-flight characteristics are controlled to conform with selected criteria can the resultant post-flight be accurately predicted?

5) If post-flight characteristics are controlled to conform with selected criteria, i.e. different types of vaults are performed, can patterns of change be shown across the initial phases of the related vaults?

RESEARCH HYPOTHESIS

H1: The optimum initial phase characteristics for vaults are specific to the vault.

Ha: Optimum performance characteristics are common for the initial phases of all related vaults.

SUBSIDIARY HYPOTHESES

H2: The outcome of a vault is a function of the pre-flight.

H3: The outcome of a vault is a function of the interaction between the vaulter and the horse during contact.

DEFINITION OF TERMS

The pre-flight phase: The pre-flight phase is defined as the phase of the vault in which the vaulter travels from the Reuther board to the horse in flight.

Initial contact: The moment the vaulter touches the horse. This signifies the end of the pre-flight phase.

Compression phase: The phase of the vault between initial contact and minimum centre of gravity to horse distance (Dainis, 1980).

Repulsion phase: The phase of the vault between the compression phase and loss of contact with the horse.

Final contact: The last moment the vaulter is touching the horse.

The contact phase: The phase of the vault in which the vaulter is in contact with the horse. This phase includes initial contact, compression, repulsion and final contact, and is also known as the time of support of the vaulter.

The post-flight phase: The phase of the vault in which the vaulter is in flight from the horse until a contact is made with the landing mat. Also known as the Free- or Second-flight phase.

The initial phases: These phases of the vault include all those up until the post-flight phase.

Layout Squat Vault: (Figure 1) 'Jump, body stretched above the horizontal before contact of the hands, pass the legs flexed and together between the arms, stretch body before the dismount (landing) to stand rearways.' (I.G.F. Code of Points, 1970)

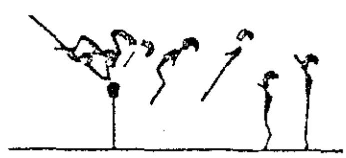


Figure 1
(I.G.F. Code of Points, 1970, p.12)

Handspring Vault: (Figure 2) 'Jump, body and arms stretched to an inverted support sideways, (descend) free to stand rearways.' (I.G.F. Code of Points, 1970)

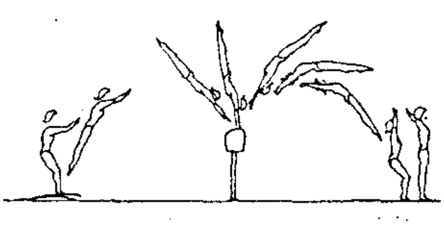


Figure 2
(I.G.F. Code of Points, 1975, p.13)

Yamashita Vault: (Figure 3) 'Jump, body and arms stretched to an inverted support sideways, turn forward, through a piked (flexed) position and straighten the body after leaving the horse landing rearways.' (I.G.F. Code of Points, 1970)

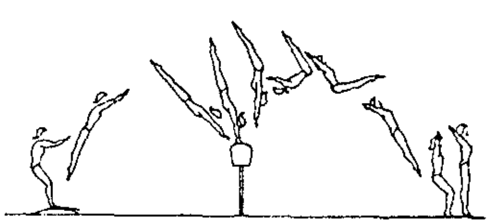


Figure 3
(I.G.F. Code of Points, 1975, p.13)

<u>Handspring Front Somersault Vault</u>: (Figure 4) Jump, body and arms stretched to an inverted support sideways, turn forward with a $1\frac{1}{2}$ tucked somersault and straighten body to land rearways.

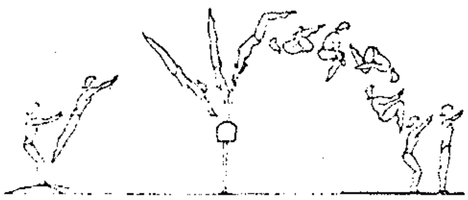


Figure 4
(I.G.F. Code of Points, 1975, p.17)

CHAPTER 2

REVIEW OF LITERATURE

CHAPTER 2: REVIEW OF LITERATURE.

INTRODUCTION

This review contains two sections, the first relates to the mechanics of vaulting and the second to techniques involved in experiments which analyse vaulting and other similar skills.

Both men's long-horse and women's side-horse vaulting are reviewed, for while it is realized that there are differences between the sexes in vaulting technique an evaluation of both gives a better understanding of the mechanics of vaulting than either would by itself.

Research in the area is not extensive but all that could be located (see Ch.3 :Procedure) has been reviewed. This includes a study by Dainis (1979) that approaches more closely than any other, the work attempted in this study, but without meeting or indeed purporting to meet the specific goals here established. All these papers report the use of cinematography to obtain the descriptive and kinematic data required. Methods of analysis ranged in them from descriptions of movements to mechanical analyses, but few developed their thesis sufficiently to explore properly the ways in which mechanical principles were applied.

Other selected articles included in the first section have a biomechanical bias but being intended for popular magazine consumption they generally lack scientific rigour, relying largely on visual observations and opinion for their starting premises.

The techniques for analysis used in the scientific papers are reviewed in the second section, along with others which have analysed similar skills.

SIDE AND LONG HORSE VAULTING

Side-horse vaults may be classified into three categories (Bowers, Fie, Kjeldsen and Schmid, 1972) these are : bent hip, where the gymnast is in a tucked or piked position during the pre-flight; layout, where the gymnast is usually stretched during pre-flight and can contact the horse in a horizontal, diagonal or vertical position; and finally twisting, where a twist about the long axis of the body is performed during the vault. The vaults in this study are all of the layout type and are from the diagonal or vertical sub-categories.

The layout squat vault has a diagonal contact position. This vault belongs to a small family of vaults in which the forward rotation initiated at take-off is changed to backward rotation during horse contact. This is generally one of the first vaults that a gymnast learns (Hay, 1978).

The Hecht vault is also a member of this family, but is a more complex vault requiring a straighter body, with perhaps a slight pike permissible during horse contact (Taylor, Bajin and Zivic, 1972).

Forward rotation in pre-flight is initiated from the pivoting effect of the body about the feet, where the gymnast is said to land with the centre of gravity behind the feet, and rotate over them to a position with the centre of gravity in front of the feet prior to take-off (George, 1971). The rotation may also be increased, in theory, by applying an eccentric thrust behind the centre of gravity in the final stages of take-off (George, 1980).

George devotes a chapter in his book "The Biomechanics of Women's Gymnastics" (1980), to the mechanical principles involved at take-off and to the trade-off effects between obtaining lift and rotation, while still maintaining sufficient horizontal velocity. These principles apply to take-off from both the board and the horse and few studies can be found which interpret their results in terms of these principles.

One such study, however, was by Slater (1960). He examined the forces at take-off using the reverse dynamics approach, and determined that the development of linear momentum was consistent, but not so for angular momentum due to the several methods which may be employed to develop angular momentum over a short period of time.

In an early study of Hecht (also referred to as Swan) vaults Guerra (1968) found that better vaults, evaluated by judges during a competition, were characterized by a greater range of angular displacement of the centre of gravity while in contact with the board. He also found that they had a larger take-off velocity, higher contact angle with the horse and a greater rise in the centre of gravity after last contact with the horse, than gymnasts who were awarded lower scores. However, his gymnasts were constrained by the rules at that time, which placed equal emphasis on the pre and post-flight phases.

More recently the requirements for both the layout squat and the Hecht vaults have changed. For women they state that the contact angle should be above the horizontal (I.G.F. Code of Points, 1975, 1979).

Hendershott (1974) reported cases where gymnasts who contacted at 45° and had a low post-flight received higher scores than those who contacted at 30° and had a good post-flight. The angle of horse contact is an important factor in performing vaults of this type. If the angle is too high the gymnast will not only have a greater amount of angular momentum to reverse, but will be in a poor position to do so, having a great degree of shoulder flexion. (Bajin, 1971; Hendershott, 1974; Bollen, 1978). In order to reverse the direction of angular momentum the gymnast must try to extend his arms at the shoulder and apply a force with the hands in a backward and downward direction. The greater the angular momentum the more the repulsion must be directed backward, thereby reducing the ability to obtain lift (George, 1980). However, it may be that the turning effect of the force during compression has a major role in reversing the angular momentum.

Present day judges place less emphasis on a high contact angle and do not make any deductions if the angle is above the horizontal, rather they look for a good post-flight (M. McLoughlin, personal communication).

The ability to obtain lift from the horse is therefore an important factor in vaults of this type, especially in the Hecht vault where the gymnasts' straight legs must clear the horse. Since the gymnast's moment of inertia is greater in the early post-flight phase of this vault than in the layout squat vault, he is faced with the additional problem of having enough rotation to land correctly. It is thought that he could either achieve a greater change in angular momentum or obtain greater lift from the horse and thereby have a longer flight time in which the rotation can accur. Hay (1978) suggests that the latter takes place since an increase in angular momentum without an increase in lift would cause the gymnast's feet to hit the horse. This higher post-flight can be brought about by a lower pre-flight with the centre of gravity still moving upward at horse contact. Hay continues...

> Because the reaction to the forceful downward and backward thrust... does not have to markedly change the direction in which he is moving, the velocity with which he leaves the horse is much greater than it would be if his center of gravity had been moving downward as his hands landed. (p.302)

George (1971) has called this the 'staircase effect' and looked at its application during Reuther board contact where the gymnast approaches the board from a low hurdle with the centre of gravity moving upward to contact the board. This effect is an important principle to be considered in vaulting, since obtaining height in post-flight, without undue loss of distance, is considered to be one of the most important requirements in present day vaulting (George, 1980; Hay, 1978).

Handspring Vaults. This same staircase effect has been found to be important during horse contact (Dainis, 1979). Handspring vaults, which were the vaults Dainis studied, differ from layout squat vaults in that they pass through the vertical position and the rotation continues in the same direction throughout the vault.

A score based on the kinematics of the entire vault was correlated separately with each variable, and a correlation matrix involving all variables was formed. Vertical velocity at horse contact appeared to be the most important determinant. However, because the score included pre-flight variables it tended to mask the effect of pre-flight on the outcome of the vault. This was a major drawback since Dainis found that angular velocity during pre-flight correlated significantly with post-flight horizontal displacement, velocity and vertical velocity, but not with the overall performance as determined by the score. This presumably occurred since a high angular velocity in pre-flight is the consequence of a short, low pre-flight which in turn is necessary to reduce the decrease in vertical velocity but which generally results in a low score being awarded.

These findings are in direct contrast to those reported by Ferriter (1964). Four of her six gymnasts had a longer and higher centre of gravity trajectory in pre-flight than in post-flight and the better vaults were characterized by a greater horizontal displacement in pre-flight associated with a negative vertical velocity at horse contact. Cianfarini (1974) has also described vaults with similar characteristics. But, of course, these vaults were constrained by the rules. In a study of men's handspring vaults Guerra (1968) found that take-off velocity, horse contact angle, height of centre of gravity above horse at initial contact and support time correlated significantly with the judges' score. He also found that their scores correlated significantly with height and distance in post-flight. This type of vault then is similar to the dynamic type analyzed by Dainis (1979) as distinct from the 'handspring-drop' vault analyzed by Ferriter (1964). These early studies (Ferriter, 1964; Guerra, 1968; Cianfarini, 1974) have described and analysed the vaults of the time without explaining the results or relating them to mechanical principles.

George (1980) suggests a decreased board-horse distance for the handspring vault, compared with the layout squat vault, to flatten the pre-flight. He also recommends a greater horizontal velocity and forward momentum. These recommendations, based on our experienced eye but without objective support from particular investigation, appear to be in line with Dainis' and Bruggemann's (1979) findings. A high and long pre-flight and a contact angle approaching the vertical have been suggested (Taylor et al, 1972) as necessary to optimise post-flight. Other suggestions are that to gain maximum lift from the horse the gymnast should contact at approximately 45° and depart near the vertical (McLoughlin, 1980; Dainis, 1980). It is not clear from the available material which angles, if any, afford the best lift without also having a detrimental effect on rotation and horizontal velocity.

In developing a model for handspring vaults Dainis (1980) has divided the horse contact phase into two components: compression and repulsion. During the compression phase the centre of gravity of the gymnast moves towards the hands whilst continuing to rotate about them. The repulsion phase, where the gymnast pushes himself away from the horse is considered to be of little importance in gaining lift. In a preliminary study of a handstand, pushing forces on a force platform were examined. Dainis found that girls could only exert a maximum static force 30% above their body weight. Whether this is an appropriate measurement is, of course, arguable. In vaulting the effort is dynamic, and the compressive phase may place muscles on stretch and elicit additional rebound forces and so increase this value. Dainis did not take this into consideration and argued that the lift from the horse cannot be aided much by such pushes and will be more effected by the centrifugal forces caused by the rotation of the gymnast. He points out that this is not the case where, in a poor vault, the gymnast has insufficient rotation about the horse and needs to spend longer in contact in order to be able to exert a greater force, a theory supported by his earlier study (Dainis, 1979) where pre-flight angular velocity was significantly and positively correlated with post-flight variables and negatively with duration of horse contact. Dainis (1981) has since verified this model using kinematic and derived kinetic data from cinematography.

The lift obtained from the horse in vaults which pass through the vertical is thought to be obtained through shoulder girdle elevation after initial compression (George, 1980). Some gymnasts have been noted to use vigorous trunk flexion from a hyperextended position, developed in pre-flight and accentuated during compression, in order to obtain greater lift (Fukushima, 1974; Warren, 1977). Others contact the horse with bent legs and extend them in an upwards direction during repulsion. These latter techniques may cause deduction due to poor body configuration (Hughes, 1976). George (1980) suggests that the push should be in a forward and downward direction in order to gain maximum lift and increase forward rotation, as the centre of gravity passes over the hands. This is in slight disagreement with the technique suggested by Hay (1978), where the gymnast pushes vertically downward, but the centre of gravity is forward of the hands. Both of these techniques will serve to increase the lift and forward rotation of the body, but the question should be asked, by how much does the gymnast need to increase his forward rotation, if at all ?

The Yamashita differs from the handspring only in that the body pikes vigorously after loss of contact with the horse and then extends immediately afterwards to land in a stretched position. This piking action has the effect of making the post-flight angular momentum requirement less for this vault than the handspring. Hay, Wilson Dapena and Woodworth (1977) calculated the angular momentum for a Yamashita over the long horse and found values of $60.28 kg.m^2.s^{-1}$ and $30.35 kg.m^2.s^{-1}$ for pre and post-flights respectively. While the angular displacement in this vault is approximately the same as for the handspring, the angular momentum in post-flight must be less due to the pike. This has led Fields (1975) to suggest a horse contact angle of not greater than 45^o.

The Yamashita existed before the emphasis on pre-flight was lessened. Donovan (1971) suggested that the gymnast should contact the horse just short of the vertical and that "there is very little push that can be exerted upon the horse" (p.23). The vault described here is very similar to the 'handspring-drop' analysed by Ferriter (1964). Vanis (1965) has analysed a similar type of Yamashita vault.

More recently Bajin (1976a) compared the performances of several world-class vaulters performing the Yamashita. He found that height in post-flight and the amount of hip flexion in the pike correlated well with the judges' score. Correct timing and amplitude of hip flexion is important in performing this vault well (Hay, 1978) and largely determined, according to Bajin (1970) by the angle at which the gymnast departs from the horse. In a study of six male vaulters he found that those who left the horse well past the vertical piked too late in the post-flight to prepare for landing. He recommended that contact angles around 45^{o} and take-off angles near vertical produced the best results in post-flight. Warren (1978) also suggested a lower contact angle for the Yamashita than for the handspring.

Hatano (1976) has studied the three vaults so far discussed; the layout squat, handspring and Yamashita vaults. He used cine techniques to calculate the path, velocity and acceleration of the centre of gravity and various take-off and contact angles. From the acceleration values he estimated the average force exerted by the gymnast during horse contact. The results are difficult to interpret since he uses no statistical analyses and made no distinction between the compression and repulsion phases. His conclusions tend to reflect these shortcomings. With regard to forces during horse contact he concludes...

> The hand-push was generally directed down-forward, (angle less than 90 degrees). Certainly in no cases it was directed to down-backward in the squat vault. Only exception to this principle was the front somersault vault (YV - 1 & 2) which requires rather fast body rotation, using the opposite reaction of the hand push. (p.348)

The backward and downward push recommended by other authors (George, 1980; Hay, 1978), is an attempt to counteract the initial compressive force and change the direction of the body's angular momentum. Since it is unlikely that a vaulter will have a greater horizontal velocity in post-flight than in pre-flight, one would not expect the average contact force to have a backward component.

The conclusions Hatano draws concerning the Yamashita would appear to conflict with other authors' results and opinions concerning the amount of rotation required. However he does not relate the direction of the force to the position of the centre of gravity, it is likely that the reaction from the backward and downward push would be directed posterior to the centre of gravity thereby slowing down the rotation.

With regard to the effect of pre-flight and contact on post-flight he concluded that "the centre of gravity trajectory during the preceding run-kick-preflight, does not vary according to the vaulting stunt" (p.349). The only differences he noted between good and bad performers were that the poorer performers had a particularly long duration of hand contact on the horse, resulting in poor post-flight.

The handspring front vault is a modification of the handspring which involves almost $1\frac{1}{2}$ somersaults from the inverted position at horse take-off to land on the feet. The angular momentum requirements of this vault have not been studied to the author's knowledge. George (1980) recommends that the pre-flight be even flatter and shorter than the handspring vault. He suggests that the shoulder girdle should apply a force in a forward-downward direction to rotate further and lift the body. It would seem that mechanical principles have been applied in a sound fashion to produce this information on technique, as distinct from that given by Wiemann (1970). He recommends that given an arched support during horse contact the gymnast should push in a backward and downward direction to obtain more lift. From Fig.5 it can be seen that he translates the reaction vector from the hands to the centre of gravity, thereby ignoring the negative turning effect of the reaction vector at the hands. Even if

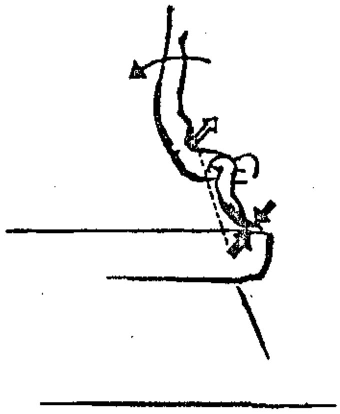


Figure 5 The reaction force at the hands: handspring-front. (Wiemann, 1970, p.11).

this effect was desirable the body is in a very poor position to exert a force with a backward component at the hands. In this position of almost full upper limb flexion with the arms remaining straight the extensors of the humerus have a very poor line of pull. This situation is similar to that described for the layout squat vault where the contact angle is high.

Hughes, writing in 1976, summarized the situation at that time when the men, but not yet the women, had changed their rules concerning pre-flight. He recommended that pre-flight angular momentum for diagonal vaults should be small, greater for vaults involving 360° rotation in the same direction and be highest for those involving 720° rotation. Concerning trajectory during pre-flight he considered that the old requirements of high and long pre and post-flights were mechanically difficult if not impossible to achieve. By altering their rules to specify only horse contact angle the men allowed their pre-flight to be of any length or height. He noted that in international competitions the better women vaulters were using a lower pre-flight without penalty since their post-flights were higher than the other competitors. The women's rules were changed soon afterwards to allow for this new style, but the present day Code of Points (1979) still has up to .05 deduction for insufficient pre-flight. Fink (1974) expressed the opinion that any insufficiency in pre-flight will be reflected in post-flight and that vaults should be evaluated in terms of height and distance in post-flight.

In summary, then:

1) There are widely differing opinions about what constitutes good technique in vaulting. Few of these opinions are based on evidence gathered under properly controlled and experimental conditions, but rather are based on practical coaching experience.

2) Discrepancies in the judging of vaults frequently reflect the

different beliefs in the possibilities of achieving good performances given some preceeding pattern of performance.

3) Changes in technique that have occurred tend to outdate some studies into the mechanics of good vaulting technique.

4) Horse contact forces and the part they play in vaulting have not been examined despite the many firm statements made about their required magnitude, direction and importance.

CINEMATOGRAPHIC TECHNIQUES

Introduction

Cinematography, widely used to study human movement (Atwater, 1973), is the classic method introduced over a hundred years ago by Muybridge and Marey (Muybridge, 1887; Marey, 1894 cited by Jones, 1952). The method has the advantage of employing a recording procedure remote from the performer who is free of encumberances such as body mounted movement transducers. This is especially useful for analysing activities which involve large or complex displacements where the interaction of the instrumented performer and his equipment could lead to entanglements of hazards. It is also genuinely useful by being an unobtrusive method that does not unduly produce inhibitions or modifications in performance.

A disadvantage of film analysis is the amount of time necessary to digitise and handle the volume of acquired data. For instance, a 1.5 second performance at an average filming speed of 64 frames per second produces ninety-six frames. As each frame may require eleven data points to be measured this will give a total of one thousand and fifty-six points for each performance of the skill. This problem has been significantly reduced by the development of partially automated motion analysers and their interface with high speed computers which now gives the research worker a range of data analysis equipment from which to choose when analysing data.

Principles governing the collection of information

Certain principles need to be followed in order to obtain an accurate representation of the movement and to minimize errors that are inherent in cinematography. Miller and Nelson (1973) suggest ways of minimizing parallax errors, obtaining a clear image and an accurate record of the movement, using two-dimensional cinematography. Among these are:

1) The plane of movement of the performer should be at right angles to the camera.
2) The camera should be as for away from the action as possible using a telephoto lens to increase the size of the image, thereby reducing parallax errors.
3) The camera should be stationary and sighted on the centre of the action.
4) Horizontal and vertical reference markers should be included in the filming and the background should be plain.
5) The subject should be performing under as near normal conditions as possible.
6) An accurate timing device should be placed in the field of view in order to calibrate the filming rate of the camera.
7) A scale of known length should be placed in the field of view in order to convert image measurements to real distances.
8) The frame rate should be high enough to prevent the blurring of rapidly moving segments.

This latter point requires further discussion since it is exposure time rather than frame rate by itself that will determine the clarity of the image. The choice of exposure time will depend upon the speed of the movement being studied. Jones (1952) suggests that a movement of no greater than 1% of the total field width during the exposure time will prevent blurring. The speed of the movement will, to a large extent, determine the type of camera to be used, since exposure time is the combination of both frame rate and degree of shutter opening.

Slow-motion vs. high-speed recording

Slow-motion and high-speed cameras film at speeds higher than the normal projection rates, but differ fundamentally in the way they move the film through the camera.

In slow-motion cameras the film moves intermittently, it is stationary as the film is being exposed and moves onto the next frame while the shutter is closed. A pin register, through the sprocket holes at the side of the film, holds the film securely in position as it is being exposed.

Due to the intermittent nature of this type of camera it is limited to a rate of 300 frames per second, beyond which the film starts to tear or buckle in the gate. Cameras of this type include those which are spring or motor-driven. The motor-driven variety is more likely to maintain a constant frame rate than the spring-driven, where the tautness of the spring will influence the speed.

High-speed cameras film at rates over 300 frames per second. They use a continuously moving film and rely largely on rotating optical parts usually mirrors or prisms to compensate for this movement. The image is transmitted onto the sensitive surface as it moves, by means of the rotating device synchronized to hold the image stationary on one frame of the rapidly moving film.

Research in biomechanics rarely requires a filming speed of greater than 300 frames per second, but with one regular exception, the study of rapid impacts.

Consequently use can be made of pin registered cameras, which generally provide the better images (Chesterman, 1951; Miller and Nelson, 1973; Robertson, 1980) and are generally available with an adjustable shutter.

An unnecessarily high frame rate provides redundant information; increases the time and effort needed to reduce the data; increases the costs involved both in equipment and film and in general will provide no more clear an image.

Frame rate determination

Cureton, writing in 1939, listed similar principles to those given by Miller and Nelson (1973), but these were limited by the technology available at the time, i.e. he recommended that the frame rate should be calibrated by dropping a ball from a known distance. This technique was also used among others by Hatano (1976). The method cannot be recommended. It is difficult to employ without additional assistance when actually filming, and determining the starting instant can be a subjective procedure.

For these reasons others who have analysed gymnastic performance, (Guerra, 1968; Ferriter, 1964), have used more accurate timing devices. Guerra filmed an electronic counter prior to filming the performer and found an error of not greater than ± 0.0004s in .0156s. Reassured he felt justified in assuming that the camera was operating at a constant 64 frames per second during his recording sessions. Ferriter (1964) made no such assumptions. She included a previously calibrated clock in her field of view while filming and used it to determine the time intervals between frames.

Dainis (1979) and Slater (1960) give no details of frame rate calibration and apparently assumed that the manufacturers' specifications were as accurate as ball dropping procedures. Unfortunately whether they were justified cannot be determined for they do not report taking precautions to minimize timing errors, precautions that might be considered not unimportant in view of their practice of differentiating the displacement data to produce velocity values.

Data analysis methods

Data transcription

Methods for analysing the data vary according to the time at which the study was undertaken. Slater (1960) traced successive images projected onto a screen, but short circuited any segmental analysis procedures by using the reaction board to determine the centre of gravity of his subjects. The path of the centre of gravity was then drawn and from this velocity values were calculated.

A similar tracing technique was used by Ferriter (1964), but to produce data in the reverse direction. She approximated the position of the centre of gravity in the first and last frames of free-flight with the use of a 360^{o} clear protractor and then used equations of parabolic motion to calculate the path of the centre of gravity over the intervening frames. This neat technique however depends upon the accuracy of judgements at those two nodal points and any errors here would be reflected throughout the flight phase on each frame with no intervening measurements offering opportunity for correction.

The first application of advanced digitising techniques in vaulting was by Guerra (1968) who used a Vanguard analyser. This enabled segmental end-points to be located to within $^{1}/_{1000}$ th inch, no information is given concerning the magnification to normal size. However Guerra did not make full use of the data he had collected for he located the centre of gravity of his subjects by estimating it to be slightly above the iliac crest. He justified the error involved by stating:

> The path of the vaulter's centre of gravity comprised a horizontal distance of approximately 20 feet. Therefore, any slight error of estimation along the path in relation to the large distance travelled would be insignificant. (p.16)

He neglects the fact that he is compounding these errors in his velocity calculations, since the change in vertical displacement is much less than 20 feet, and that as path variation is the determinant of success or failure in a vault, which is not a long jump event, errors should be measured relative to these variations.

Dainis (1979) was the only investigator to use a smoothing technique, a quadratic function, to reduce his random errors. He employed a Numonics 1224 digitiser linked directly to a computer, calculating the centre of gravity of his subjects by the segmental method.

Segmental analysis

This technique determines the centre of gravity of the body by summing the moments of the individual segments about a fixed reference point. Dainis (1979) used this technique with three segments (trunk, upper and lower extremities) and used data from Dempster's (1955) study, as presented by Plagenhoef (1971). He could not find any available data concerning the segments of young female gymnasts. However Plagenhoef (1971) presented data from Kjeldsen (1969) concerning female gymnasts and more recently Cook (1978) has produced results using the water tank displacement method to calculate the percentage mass of female gymnasts' segments. Johnson (1976) has also published data relating to the location of the segmental centres of gravity in females. However Dainis (1981) considers that Dempster's values are better suited to his subjects than any segmental data concerning adult females. This is of course arguable and Dainis (1979) has had to adjust the position of the centre of gravity along the longitudinal axis of the body in order to achieve minimum horizontal acceleration.

This highlights the importance of selecting segmental data which are as appropriately as possible matched to the characteristics of the performer e.g. same sex, age, size and body type; or perhaps using predictive equations similar to those developed by Clauser, McConville and Young (1969) when they become available for women.

Once the centres of gravity had been calculated Dainis used a least-squares quadratic function to smooth the horizontal and vertical displacement data. He did not attempt to estimate his errors beforehand.

Error reduction procedures

Various methods are available to reduce errors by smoothing displacement data. Smith (1975) lists some problems which are likely to lead to errors in gathering data from film, and recommends certain techniques to remove the noise due to error. Other methods of smoothing are also listed in Chatfield (1980), Winter (1979) and Miller and Nelson (1973). These include:

1) Smoothing the raw data by eye. A subjective method whereby a curve of 'best-fit' is drawn through or close to the points.
2) Moving averages, which is a linear filter to smooth out local fluctuations and estimate the local mean, usually over 3, 5 or more values.

3) Polynomial smoothing. In these more objective methods a computer may be harnessed to 'best-fit' the curve through the digitised points.

The mathematical equation of the polynomials, now most usually adopted for this smoothing process gives the least squares of the residuals (Winter, 1979; Negus, mimeographed material; Widule and Gossard, 1971). Of course, although this technique is not subject to human judgement in the actual fitting process, it is in selecting the degree of polynomial that is to be used. A polynomial of an order that is too high for the data will follow the points too closely and not remove the noise due to error. If the order is too low then some of the actual data will be smoothed out and lost. It follows then that in smoothing data using this technique some prior knowledge of the form of the data and its error characteristics should be obtained so that the appropriate order may be selected.

Other techniques are available which are especially useful for cyclic data. These include the use of Fourier analysis and low pass filters (Winter, Sidwall and Hobson, 1974). However polynomials are considered better for non-repetitive movement, especially where the data can be expected to have the form of the polynomial chosen (Winter, 1979).

A second-order polynomial is an obvious choice for displacement data in which the performer is airborne and which is properly considered to be parabolic. However this cannot be adopted also for those phases of the movement where the performer is in contact with the ground, since rapid changes in displacement can be expected, especially during the landing (Widule and Gossard, 1971).

Spline fitting is a modification of the polynomial smoothing technique where the curve is broken into sections and an equation, often cubic, is fitted to these. A number of researchers have evaluated the cubic spline against other smoothing techniques (Zernicke, Caldwell and Roberts, 1976; McLaughlin, Dillman and Lardner, 1977). Zernicke and co-workers filmed a performer kicking whilst standing an a force platform. They compared the vertical acceleration curves derived from the displacement data which had been smoothed using either a cubic spline or orthogonal polynomial equations. They found that the 5th-order polynomial, of all the polynomials used, gave the acceleration curve that more closely approximated the force trace, but that the cubic spline provided a much better estimation, with a 95% mean agreement between the two.

McLaughlin et al (1977) also compared the acceleration curve from a cubic spline fit with the vertical reaction force trace for a standing vertical jump. They had difficulty in obtaining an exact synchronization between the film record and the instant of take-off, but still found excellent agreement between the two curves. In evaluating the cubic spline against a 5th-order polynomial for knee angular acceleration in running they found that the polynomial appeared to smooth out some of the true signal and provided unreasonable values at the end points.

The spline was also found to produce good results when compared with those obtained using the finite difference method based on the Taylor series expansions in angular acceleration during elbow flexion; and when compared to the nine-point chord average for knee angular acceleration. However the methods used here to evaluate a good curve are largely based on the expectations of the researcher, rather than on objective criteria.

In the same study (McLaughlin et al, 1977) a more objective test was performed using the spline where the vertical acceleration was calculated from displacement data of a dropped weight. The acceleration graph overshot the expected value of $9.8 m.s^{-2}$ at the end-points where it tended to zero. The authors suggest that caution should be exercised when interpreting the derivatives near the end-points of the data. They concluded that for smooth and monotonic curves a simple quadratic or cubic spline fit would appear to be appropriate.

When smoothing data to reduce errors knowledge should be acquired beforehand of the fundamental form of the data, so as to retain the essential elements of the signal while reducing the random error.

Angular kinematics

Angular displacement and velocity can also be smoothed to reduce random errors in calculations, although in all studies of vaulting this has not been the case. This situation exists because of the need to measure only specific angles such as take-off and contact, and not the whole range of motion (Ferriter, 1964; Guerra, 1968; Hatano, 1976; Dainis, 1979).

The body angle has been determined by various methods. Ferriter (1964) drew a line from the malleolus of the ankle to the ear or wrist and measured between this line and the vertical. Guerra (1968) used a similar method to determine angle at take-off and also measured the angle between the trunk and the horizontal at horse contact. Trunk angle was also used by Hatano (1976) however this angle is not appropriate for all phases of the vault due to the changes in body configuration that occur. The technique used by Ferriter (1964) is to be recommended since it more closely approximates the whole body line. Dainis (1979) drew a line between the centres of gravity of the legs and arms to determine the body angle of the gymnasts over several frames and differentiated this to produce angular velocity. However he used this information only as a check on angular velocity derived from the calculation of whole body angular momentum. He does not give any details as to the agreement between these two sets of values.

While angular momentum will be constant in free-flight, angular velocity need not necessarily be so. Dainis gives no details as to in which part of the flight phase the velocity values were calculated. One assumes he has smoothed the data by taking the average of the values calculated.

In summary, procedural guidelines recommended for adoption in biomechanical studies have been reviewed and the critical specifications required to meet the needs of this study have been identified.

SOME TECHNIQUES FOR THE MEASUREMENT OF FORCES

Introduction

In performing certain athletic or gymnastic activities the athlete must produce large changes in displacement, both in magnitude and direction. To produce these changes a force must be exerted against the ground or apparatus, usually by the feet. In vaulting, the gymnast exerts that force against the horse with the hands. By this means she influences the movement of the body in post-flight. How effective that hand contact is in determining post-flight is uncertain. It is a matter of controversy but has not yet been objectively studied.

The study of contact forces in sporting activities can give information about more effective force evoking techniques and several studies have looked at the reaction forces at the feet and their role in determining effective performance.

In general forces are measured directly by pressure sensitive devices which respond to the deflection, however minimal of the surface on which forces are being applied or indirectly by the reverse dynamics approach.

Strain-gauged equipment

The vertical reaction force between the gymnast's feet and the Reuther board was determined by Kreigbaum (1974). In a descriptive study she strain-gauged the displacement of the board and fed the output through a Wheatstone bridge circuit to an oscillograph. The equipment was statically calibrated by loading the board with weights and measuring the deflection of the trace on the U-V paper. Results obtained indicate that there are two peaks during contact. The first being the acceptance of the gymnast's weight on the board and the second due to the simultaneous extension of the hip, knee and ankle joints. Peak values were approximately 18 and 6 times body weight respectively.

The gymnasts were filmed during the take-off using a Locam 16mm camera at 180 frames per second. The centres of gravity were calculated using Kjeldsen's data (1969) and velocity values were obtained. No information is given concerning the technique used if one was used at all to smooth the data. The force traces were integrated to give total impulse. This correlated significantly with the magnitude of the second peak, but showed no relation to change in speed of the gymnast. Kreigbaum may have obtained a significant relationship had she correlated total impulse with change in momentum. However she chooses to explain this result in the following way...

> First,...part of the impulse from the board would be lost in the damping effects of the articulations and soft tissues of the body. Second, some of the impulse could be absorbed by the partial relaxation of musculature surrounding these articulations, so that the joints were not rigid connections and thus flexed in reaction to the upward force. (p.138)

Whilst kinetic energy might be absorbed under these conditions, the change in momentum should be accounted for by the impulse from the board (Smith, 1972). Discrepancies between the two must be due to either errors in calculating the velocity of the centre of gravity, incorrect records being provided from the Reuther board or the fact that the mass of the gymnasts was not taken into consideration.

Kreigbaum does not give an overall evaluation of the vaults studied, so it is not known which variations in the characteristics of the force trace were associated with improved results.

Force platforms and plates

Force platforms and plates have been widely used to study the reaction forces between the athlete and the contacting surface. They have the advantage over the technique employed by Kreigbaum in that they generally give the three orthogonal components and moments of the force.

The amount of deflection of the surface must be minimal, Paul (1975) recommends less than $^1/_{1000}$th inch otherwise it will interfer with the skilled movements of the athlete. The surface of the platform must also be rigid, in order to minimize 'cross-talk' between the force components, and this has led to problems with the natural frequencies of the system. However force plates are manufactured today which have natural frequencies advertized as over 200Hz (Paul, 1975) but which when measured are found to be over 400Hz (Soames, 1978).

Strain-gauges and piezo-electric crystals are often used to measure the deflection of the surface. The signals from several of these are fed to a bridge circuit and from there to equipment for amplification and recording. It is important that systems used to record the force continuously against time should have a low inertia (Paul, 1975), otherwise directional changes will be swamped by delayed responses and overshoots. The use of pen recorders, which have a high inertia, is undesirable (Payne, 1968) since the signal requires a rapid response and the use of an ultraviolet recorder with low inertia galvanometers is recommended.

Force platforms in sport

Force platforms have been used in the study of many sporting activities. In the field of gymnastics Payne and Barker (1976) have studied the take-off forces involved in the flic-flac (back handspring) and back somersault.

They used four good gymnasts as subjects and chose the best performance of each from several trials filmed using a 16mm camera. The film was synchronised with the force traces by means of a continuous motion clock in the field of view, which produced impulses on the force trace. The reaction board was used to determine the position of the centre of gravity to within 2cm. Prints were produced from the film and onto these the reaction vectors and the positions of the centres of gravity were drawn. These were evaluated in terms of the magnitude and direction of the reaction vector relative to the centre of gravity. From their results they concluded that common coaching and teaching instructions were well supported by biomechanical evidence of the important factors in performance.

Studies of this type and others similar, involving statistical analyses, could be of great importance to coaches and teachers, but are rarely undertaken in gymnastics.

Payne and co-workers have produced information on reaction forces relating to the sprint start (Payne and Blader, 1971), the shot putt and weight-lifting (Payne, 1974) and the tennis serve and golf drive (Payne, 1978).

Long-jump has been a popular event in studies incorporating force platforms techniques. Ramey (1973, 1974) and Bedi and Cooper (1977) have studied the angular momentum changes that occur during take-off. The moments of the horizontal and vertical reaction forces are calculated relative to the centre of gravity of the athlete and summed to produce a value for their turning effect. These evaluations have led Ramey (1974) to suggest that, although an athlete cannot significantly alter his maximum force, he can alter the position of the centre of gravity relative to the take-off foot at the approach instant to produce an optimum amount of angular momentum for a specific type of jump.

Many studies have been conducted into the forces exerted during take-off in a vertical jump. Of interest is one study by Lamb and Stothart (1976) which compares the results obtained from cine and force platform techniques in determining the vertical take-off velocity of the jump. They integrated the force trace where the value of the force was greater than body weight and compared the results to those obtained from the film, where the centre of gravity vertical displacement curves had been smoothed using a least-squares polynomial and derivatives calculated to give velocity values. They found good agreement between the forces at the feet and the change in momentum of the centre of gravity. Smith (1972) also obtained similar results when studying a drop-landing onto a force platform. He obtained two values for the change in momentum of the body, one from the centre of gravity of the system and the other by summing the changes in momentum of the segmental centres of gravity, the values were almost identical and compared well with the impulse at the feet.

In summary, some useful work with relevant applications to sports biomechanics has been reviewed. In these studies both the horizontal and vertical reaction forces invoked by the athlete or gymnast have been measured, to give a better understanding of their effects on velocity and angular momentum changes which occur.

CHAPTER 3

PROCEDURE

CHAPTER 3: PROCEDURE

OVERVIEW

Two experimental programs were undertaken. The first was in two parts:

a) to determine the characteristics for each type of vault and if these differed between different types of vault.

b) to develop equations predicting the outcome of a vault from initial characteristics of the performance.

The second was designed to validate the predictive equations in two ways:

a) with a group of good vaulters performing their best vaults,

b) with a program to examine the effect of pre-dictated variations of pre-flight characteristics on post-flight.

In Experiment 1 six vaulters were filmed performing three, and in one case four, vaults, while recording contact forces from two platforms to which the side vaulting horse was bolted. In Experiment 2 four vaulters performed three of their best vaults, one of each type was selected for analysis. Two of these vaulters were asked to introduce pre-flight variations in two of their vaults to order, but only one was able to perform these variations efficiently as requested.

A preliminary feasibility study to ascertain the nature of the records, likely distribution of measurement data and to provide realistic samples of data from which to develop the programs of analysis was conducted on six young gymnasts, filmed while performing three vaults each.

Subjects were always allowed adequate practice and warm-up before any recordings were made, and several trials were filmed before the actual recordings were taken.

Thus a total of nine subjects (one was included in both experiments) performing thirty-nine vaults were recorded. Of the nineteen vaults recorded in Experiment 1 one was omitted from the analysis because of its perceived poor standard. In Experiment 2 seven vaults were selected for analysis. Of these, the four vaults with pre-dictated variations of pre-flight were performed by a subject who had taken part in Experiment 1.

ORGANIZATION OF THE LITERATURE REVIEW

The initial location of references relating to vaulting was through of review of cine techniques in biomechanics (Atwater, 1973). The bibliographies of Hay (1974, 1976), Squire (1977) and the Sports Documentation Monthly Bulletin published by the University of Birmingham library were valuable sources of information. A search of the back issues of the monthly bulletin was conducted at the Birmingham library and a subsequent check on the issues received at Loughborough University was conducted. Regular searches were also made of current scientific journals which had previously provided information.

A search of Index Medicus using Medline under descriptors 'vault', 'jump' and 'gymnastics' revealed several articles relating to injuries in gymnastics, three articles concerning the long-jump and many relating to the cranial vault. None of these were considered relevant.

Several coaching articles had been collected by a national coach (Mr. W. McLoughlin) and the author in an ongoing current awareness program. A search through the back issues of the main gymnastic coaching journals revealed few others. Again a regular check was made of current issues.

Several papers were also collected by following up references cited in other papers, a procedure that was followed until no new references could be located.

EQUIPMENT

Photographic equipment

A Bolex H16 Reflex spring driven camera was used in the collection of film data. This camera has a variable shutter and framing rate and can be used with either a 50mm, 1.8 or 25mm, 1.4 lens.

The framing rate was set at 64 frames per second and the shutter in the 'half-closed' position, this gave an opening of 72^{o} and an exposure time of $^{1}/_{320}$ second. This time was brief enough to prevent blurring of the limbs during their most rapid movements.

A cable release was attached to the camera and used in the filming in order to avoid any movement of the camera.

Kodak 16mm film both Video News Film (daylight, colour, ASA 160) and Tri-X Reversal (daylight, black and white, ASA 200) were used for the filming.

A Hulcher 35mm sequence camera was used to take a series of still pictures at time intervals of $^{1}/_{25}$ second. This camera was used with a remote shutter control.

A Weston light meter was used in conjunction with both cameras.

Ancillary equipment used in the photographic procedures included a right-angle metre scale marked in black and white intervals with 8cm black and white targets attached to the ends; a conical timer, which is a rotating cone based on the design of Blievernicht (1967) driven by a gramphone motor. It can be adjusted to rotate at the rate of 1000ms per revolution. The cone has a height 50cm and diameter 1.01m marked in .01 second intervals and can be read accurately to within .002 seconds; and finally a Venner Electronic Counter, which has a digital display in milli-seconds.

The force platforms

The force platforms used in this study are those described by Payne (1974) and designed and constructed by Payne and Blader, based on the design of Cunningham and Brown (Payne, 1975).

They are two identical cantilever type platforms constructed with a strain-gauged cylindrical post in each corner, supporting a cast-iron frame and 15cm of aluminium honeycomb. These platforms measure the three orthogonal components of the force, as well as their moments. In this experiment only the vertical (Z) and the horizontal force (X) were recorded.

The signals from the strain gauges are fed into a Wheatstone bridge circuit which sums the values of each component. These voltages then pass to an amplifier (4000 system, S.E. Laboratories Ltd., SE 4300) which is linked to an ultra-violet (U-V) recorder (S.E. Laboratories Ltd., type SE 2100). This recorder uses low inertia galvanometers, whose positions vary in accordance with the current and deflect the beams of light accordingly onto photo-sensitive paper. Kodak Linagraph direct print paper (standard type 1895, 30.5cm wide) was used to record the traces.

A continuous motor clock driven by a mains frequency synchronized motor was connected to the U-V recorder to produce four pulses in a regular cycle of .02 seconds on the paper. This clock has a sweep needle that rotates at the speed of 5 revolutions per second. The face of the clock is marked at ten regular intervals and can be read accurately between these .02 second intervals.

The integrating instrument

A Haff Planimeter (No. 317) which measures in square centimeters was used to integrate the force traces.

The Vanguard analyser

A Vanguard X-Y analyser was used to digitise the points from the film.

The analyser consists of a backprojection screen onto which the picture is projected after being reflected by a mirror. The projector has a frame counter and pin register to ensure the exact location of each frame in the gate.

A double plate perspex cursor moves horizontally and vertically across the screen to the desired point. This point can be accurately located without parallax error by superimposing two coincident sets of fine lines drawn on the parallel perspex plates. The cursor locks into position while the reading is being taken.

A Minc Computer was linked to the analyser, and with the use of a standard program (VANGRD: R. Buxton), upon depression of a foot pedal the X and Y coordinates were entered into a file on a floppy disc in the computer. A digitising rate of one coordinate pair per 2 seconds is feasible, but on average a workable rate was found to be one point per 4 seconds.

The computers

The ICL 1904S computer located in the Computer Centre at Loughborough University was used to transfer the data from the floppy disc to the Prime system. This required the disc to be read into the ICL 1904S and then two programs (FLOPPY TRANSFER JOBS 1 & 2: R. Thirlby) were run to transfer the data onto a file in the Prime system. Use was also made of statistical packages available on the ICL 1904S.

The data was analysed using the Prime, a system which consists of two 1280K byte Prime 400 processors, 620 Megabytes of disc storage, a magnetic tape deck compatible with discs on the ICL 1904S and other ancillary equipment. It is an interactive system linked to terminals spread throughout the campus. There are several types of terminals available for use, these include Trend printers, V.D.U.'s and a Sigma S5660 colour V.D.U.

Gymnastic apparatus

The vaulting horse was set at the regular senior competition height of 1.20m., and anchored firmly to the ground to avoid any movement as the gymnast made contact.

The springboard used is commercially available and manufactured to meet the specifications of the Apparatus Booklet (I.G.F., 1979).

THE SUBJECTS

Selection of subjects

The nine subjects used in this study were selected according to their vaulting ability from two English clubs. The gymnasts were from International, National or Regional Zone squads and considered by their coaches to be good vaulters. The group was considered to be fairly homogeneous since the two coaches worked together closely and taught the same techniques.

Preparation of the subjects

Black electrical tape was cut into strips of suitable lengths, 3 - 10cm, which were used to mark the joint centres as described by

Dempster (1955) and Plagenhoef (1971). Crosses were attached to the subjects and a white dot of 1cm diameter was placed in the middle. Joints marked in this manner include the ankle, knee, hip and shoulder. Because of the flexion of the arm during the vault, two landmarks were placed on the shoulder, one 5cm below the acromion process and the other 3cm above the posterior fold in the axilla. A radiograph was used to determine the distance for this method, (see Fig. 6) since it was thought that the 8cm distance from the 1st rib, recommended by others (Plagenhoef , 1971; Lees, mimeographed material) is both difficult and awkward to locate and measure. Longer strips of tape were placed along the line of the plane of the joint axis. The rotation of the arm about its longitudinal axis during the movement required that the plane of the joint axis be marked for the elbow and the wrist, dots were placed on the medial and lateral epicondyles of the elbow and the styloid process of the wrist.

In order to locate the joints between C7-T1 and T12-L1, during the digitising, thin strips of polystyrene, with black tape wound around at 1cm intervals, or black electrical tape folded and with a white dot on the end, were attached to the skin or leotard of the subject.

Weight was recorded using previously calibrated balance scales (Salter, Birmingham; Avery, St. Mary's; Herbert & Sons., Loughborough) with the subjects wearing the sleeveless leotards and any light, flexible footwear worn in the experiment. Weight was recorded in kilograms or pounds to the nearest 0.1kg. or 0.25 pound and converted to kilograms.

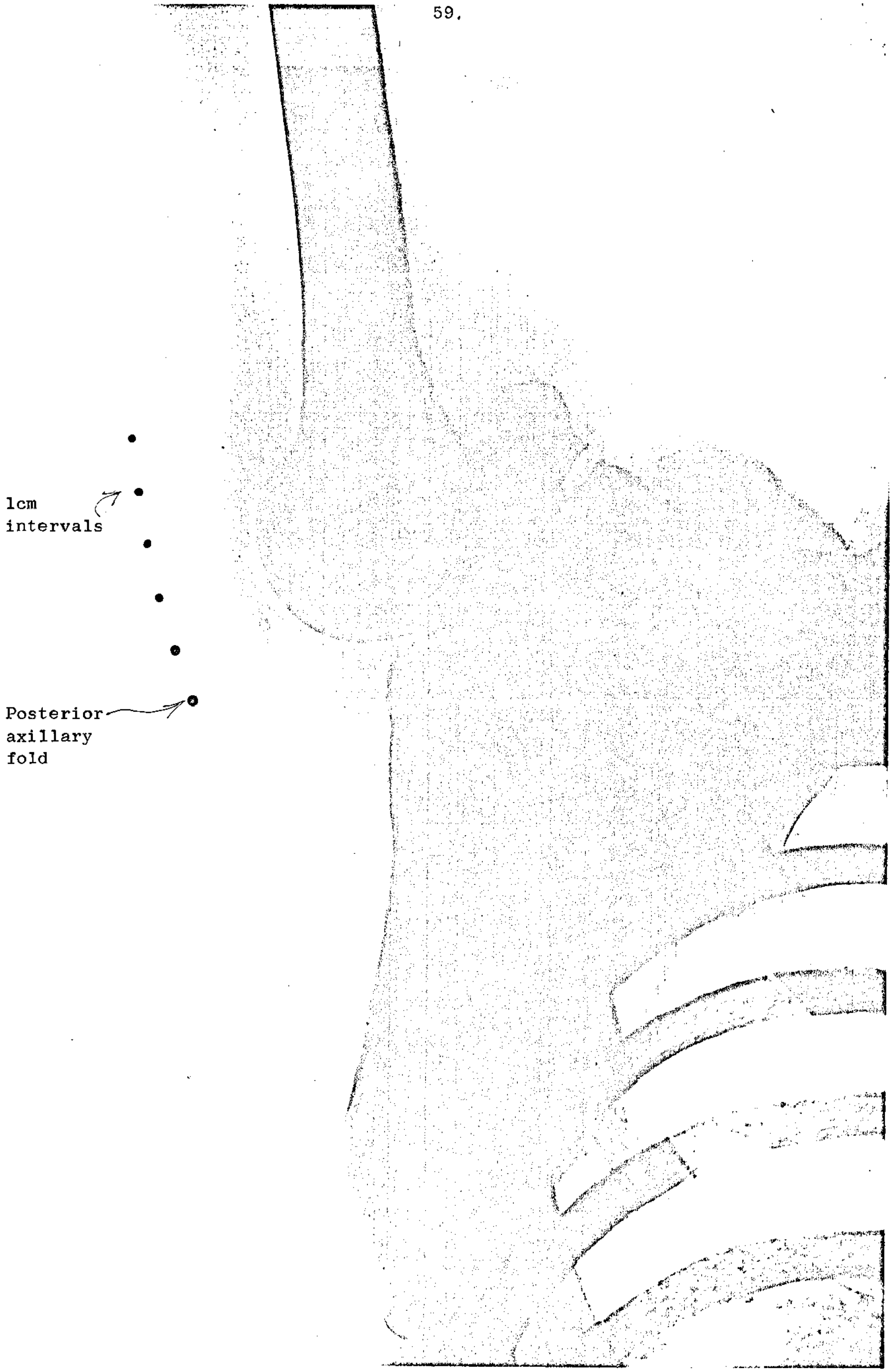


Figure 6. Determination of the location of the shoulder joint centre relative to the posterior axillary fold.

Stadiometers were used to measure the height of the subjects. The subjects stood with the back, buttocks and heels against the stadiometer, while the head was kept in the Frankfort plane. Upward pressure was exerted against the mandible and styloid processes, while the heels remained in contact with the ground. The reading was taken from the scale in millimetres.

EXPERIMENTAL AREAS

Outdoor sports field, University of Birmingham

The first experimental test session was conducted on the 'red-gra' area of the outdoor sports field at the University of Birmingham. The force platforms were located centrally in this area, in a specially designed concrete pit. They lay side-by-side giving a total surface area of 152 x 76cm^2. Two pieces of 1" thick blockboard were screwed to the surface of the platforms to bring them up to ground level. It was into these pieces of wood that the horse was firmly secured. However the location of the platforms restricted the layout of the equipment. This meant that there was virtually no limitation to camera-subject distance, however the gymnasts were limited to 14m in their approach run.

The background was composed mainly of a steeply sloping grass bank, which provided a good contrast with the subjects. It was necessary to locate the U-V recorder near the horse which detracted from the plain background, but during data transcription this proved to offer no problems.

The use of an outdoor area provided the usual organizational problems and the session was twice postponed due to inclement weather.

On the test day rain threatened, a few drops fell and it was not very warm.

A layout of the experimental area is given in Fig. 7.

Victory Hall, Loughborough University of Technology Sport's Hall, St. Mary's College, Twickenham

These gymnasia provided good conditions for the second test program. The layouts were similar to that described for the Birmingham session. They differed however in the following respects:

1. Approach run - a full 20m run was available.
2. Background - painted walls or backboards provided a good background contrast.
3. Camera-subject distance - at St. Mary's the camera-subject distance was limited to 12m and a 25mm lens was used.

STANDARDIZED TEST PROCEDURES

Experiment 1

Aim: To test the hypothesis that the outcome of a vault, reflected in measurements of the kinematic variables of post-flight, could be predicted from kinematic and kinetic variables during the pre-flight and contact phases, and if these vary between different types of vaults.

Apparatus

The cine camera was positioned normal to the plane of movement of the gymnast in line with the centre of the horse, at a distance of 15m. It was firmly secured to a solid tripod and set at a height of 1.5m. A 50mm lens was used and this enabled the gymnast to be in the field of view from contact with the board until landing, a distance of approximately 5m. Parallax error of assuming shoulders 20cm from centre line (i.e. 1.3%) was considered to be negligible.

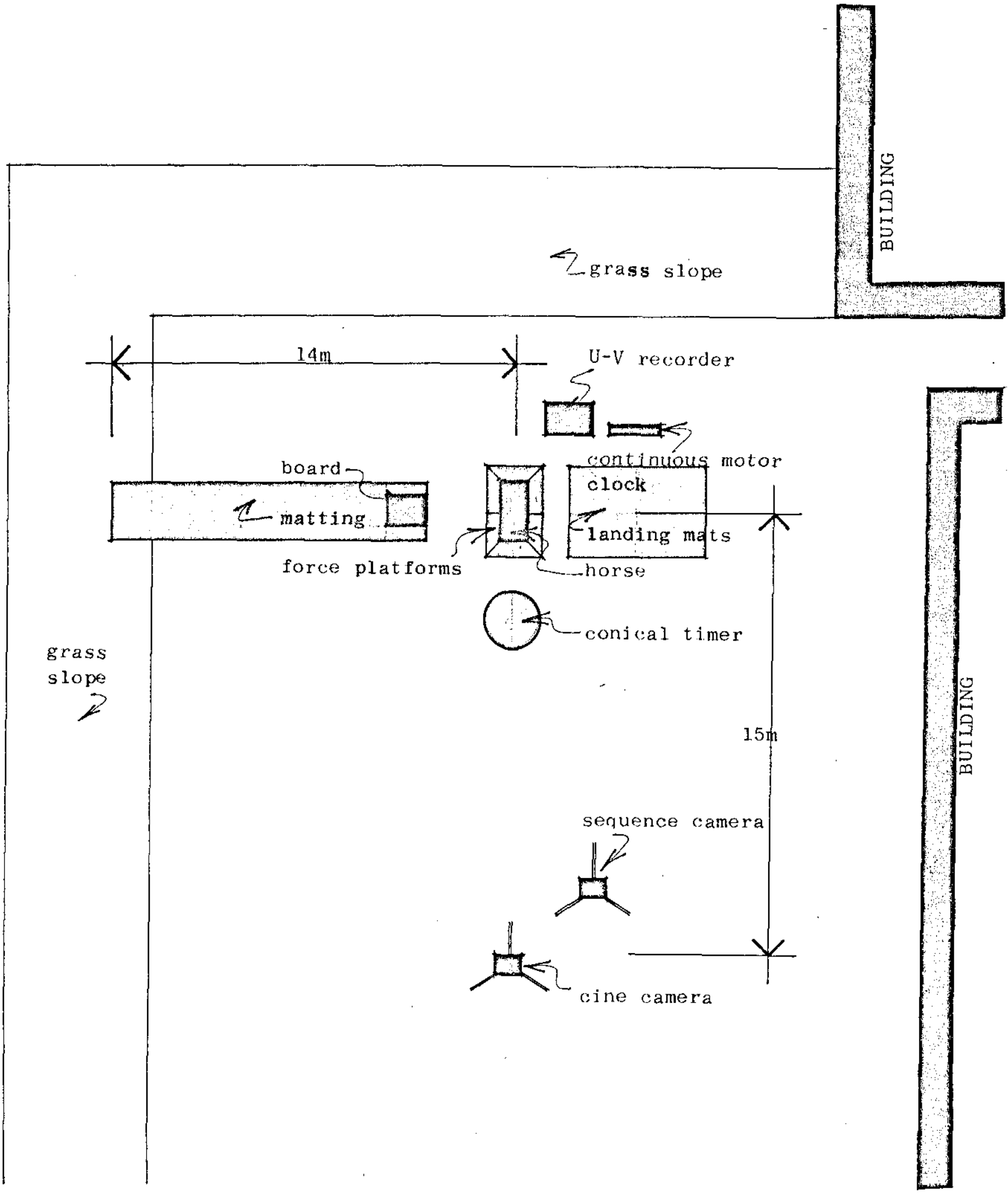


Figure 7. Diagram representing layout of equipment for Experiment 1.

The Hulcher sequence camera was similarly placed at right-angles to the plane of movement of the vaulter. However it was closer to this plane at a distance of 12m and was positioned in line with the edge of the landing mat nearer the horse.

The light metre was used at frequent intervals, as the clouds gathered and dispersed, to take light readings and calculate the appropriate f-stops.

The right-angled metre scale was placed in the vaulter's plane of movement and filmed prior to filming the subjects, so that the film measurements could be converted to actual distances. The distance between the targets attached to the ends of the scale was measured to be one metre using a metre rule. The horizontal arm of the scale was adjusted to the correct position with the use of a spirit level, marked in .03 degree intervals, but capable of greater precision in measurement. The vertical arm was checked in both planes using a plumb line.

The conical timer and continuous motor clock were also placed in the field of view and filmed during the data collection.

The force platforms were located in the pits as described and attached to the U-V recorder, to which the continuous motor clock was also linked. The horse, which had been braced to reduce the oscillations, was screwed to the blockboard on top of the force platforms. Run-up mats were provided to a distance of 14m. and thick crash-mats were used as a landing surface. The gymnasts were permitted to adjust the distance between the springboard and the horse to suit their requirements.

Preparation for performance

Prior to the test sessions all subjects were told the nature of the experiment and were asked to prepare themselves to perform their best vaults. This preparation included a general warm-up inside and then the gymnasts were allowed as many vaults as they needed in order to be performing at their best. Several of the last few warm-up vaults were filmed and forces recorded, with the subjects' knowledge, to familiarise them with the procedures and nature of the occasion ready for the moment when data could be collected.

Recording and measurement procedures

Several people were needed to organise the session and operate the equipment.

The subjects performed their vaults in a randomised order, in case the performance of a specific type of vault affected the performance of the next type. Mr. C. Acikada organised the gymnasts and told them which vaults to perform, from a previously prepared list. He also frequently checked the security and locations of segmental endpoint markers.

Mr. H. Payne operated the U-V recorder and the Hulcher sequence camera, by remote control during the performances.

The author operated the cine camera using a cable release and checked the alignment of the camera after rewinding.

After any interruptions to the session, e.g. following changes of film or U-V paper, the gymnasts were allowed two vaults to warm-up again. Figure 8 shows the layout of apparatus, equipment and personnel involved in the data collection.

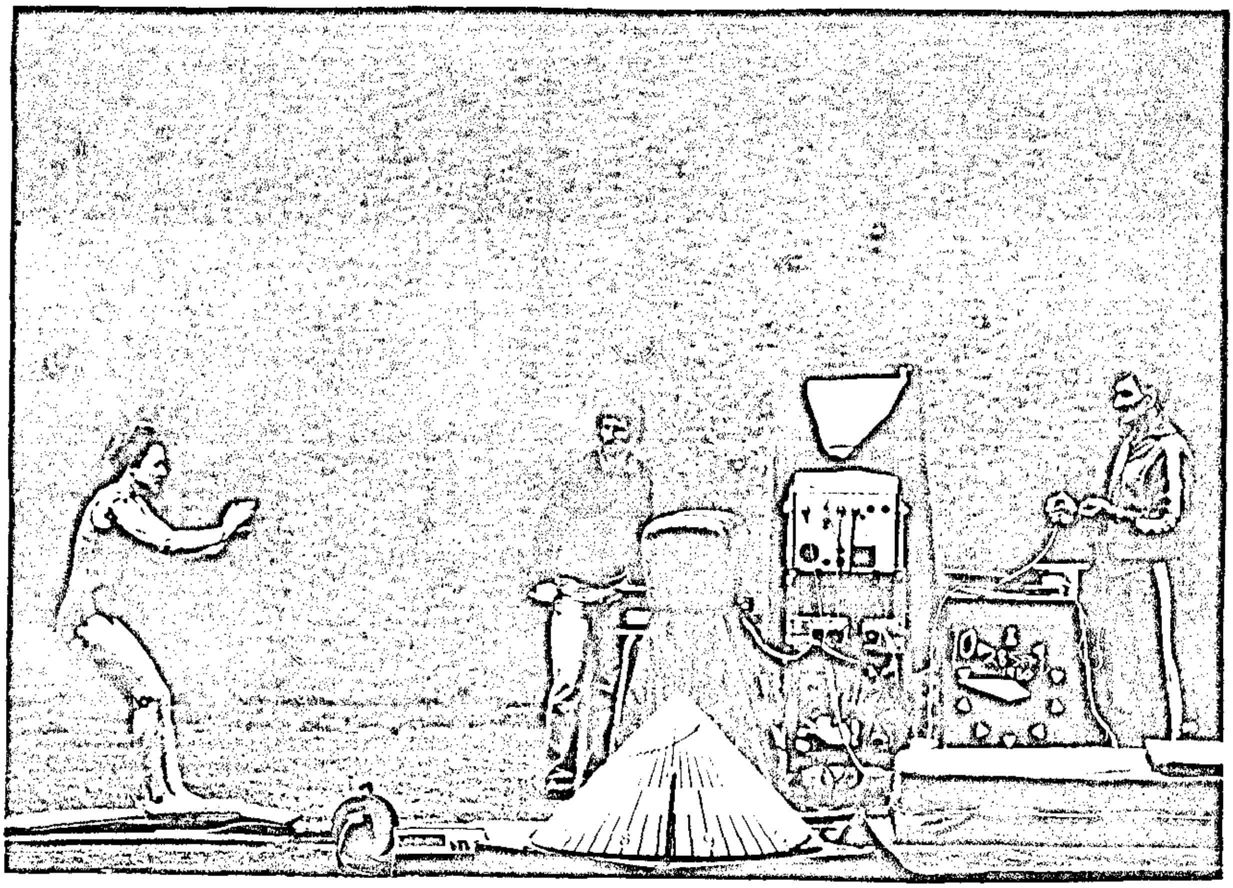


Figure 8. Layout of equipment, apparatus and personnel, Experiment 1.

Variables measured

Information concerning the following variables was collected during this experiment.

1a) Kinetic variables

Horizontal forces (lbs.)

Vertical forces (lbs.)

Time (ms)

b) Derived kinetic variables

Horizontal impulse (N.s/body mass)

Vertical impulse (N.s/body mass)

Average horizontal compressive force (N/body weight)

Average vertical compressive force (N/body weight)

Average horizontal repulsive force (N/body weight)

Average vertical repulsive force (N/body weight)

2a) Kinematic variables

Position of segmental endpoints (mm)

Time interval between frames (ms)

b) Derived kinematic variables

Displacement of the centre of gravity (m)

Angular displacement (degrees)

Horizontal velocity ($m.s^{-1}$)

Vertical velocity ($m.s^{-1}$)

Angular velocity (degrees / second)

Vertical acceleration ($m.s^{-2}$)

3) Physique variables

Height (mm)

Weight (lbs.)

The criterion variables in this study were obtained from the derived kinematic variables of post-flight. These are:

a) horizontal displacement of the centre of gravity (m)

b) change in vertical displacement of the centre of gravity from loss of horse contact to peak of flight (m)

Comments

1. The subjects were not performing under ideal conditions due to the location of the force platforms and out of doors.
2. While the records of the forces evoked during horse contact gave a general representative picture of the behaviour of the subjects, low frequency noise was also recorded due to the oscillations of the horse initiated by the compressive force.

Experiment 2

Aim: To check the validity of the predictive equations obtained from Experiment 1 outdoors on vaulting performance indoors.

Four subjects were used in this experiment. The subject who had participated in the first experiment also performed the vault with specified modifications of pre-flight.

Apparatus

The camera was located at the maximum permissible distance across the width of the gym and the minimum size lens used which would just record the required field of view.

The right-angle metre scale, light meter and conical timer were used as for Experiment 1. Two tungsten 1000 watt lights with daylight filters attached were used at St. Mary's, since the natural light was not sufficient to permit filming at high speeds.

Preparation for performance

These subjects were similarly asked to prepare themselves to perform at their best and were allowed time for both a general and a vaulting warm-up. Two of the subjects were also asked to perform the layout squat and handspring vaults with modifications in pre-flight. These modifications were to have either a high or low pre-flight, in terms of the trajectory of the centre of gravity. Only one subject (JT) was able to perform these vaults in the required manner.

Several warm-up trials were filmed.

Recording and measurement procedures

The cine camera was operated during the performance of the vaults.

Variables measured

Variables obtained in this experiment differ only from those obtained in Experiment 1 in that there were no kinetic data collected and that it was necessary to record the type of pre-flight being used in four of the vaults.

Comments

1. The use of indoor areas in this experiment provided the subjects with good and familiar conditions in which to perform.

CALIBRATION OF EQUIPMENT

Camera framing rate

In both studies the framing rate of the camera was calculated by filming the conical timer during all performances. The revolution rate of this timer can be accurately set to 1000ms with the use of the Venner electronic clock. A reed switch, attached to the rim of the large rotating cone, provided a pulse once per revolution which activated an on-off circuit to operate the Venner clock. Only minor effort was required to adjust the timer to a rate of 1000ms per revolution. Variations greater than $\pm$5ms were considered unacceptable. The revolution rate was checked at regular intervals during the experiment, see Figure 9.

A framing rate of 64 frames per second gives an interval of 15.6ms between successive frames. The resolution of the film and the image size of the timer meant that it could only be read with confidence to 2ms. This is a large error in 15.6ms, 12%, therefore was decided to take the readings of strategic frames in the vault and calculate the average time intervals for the intervening phases. The framing rate was assumed to be constant for each phase.

The continuous motor clock also used in Experiment 1 can also be read with confidence to 2ms. Both this clock and the conical timer were used to determine the duration of horse contact. The results are presented in Table 1.

The Pearson product-moment correlation coefficient between the results of the two clocks was calculated (see page 101) and found to be $r_{xy} = 0.995$. The standard error of the measurement, page 102, estimating the value of the continuous motor clock from that of the

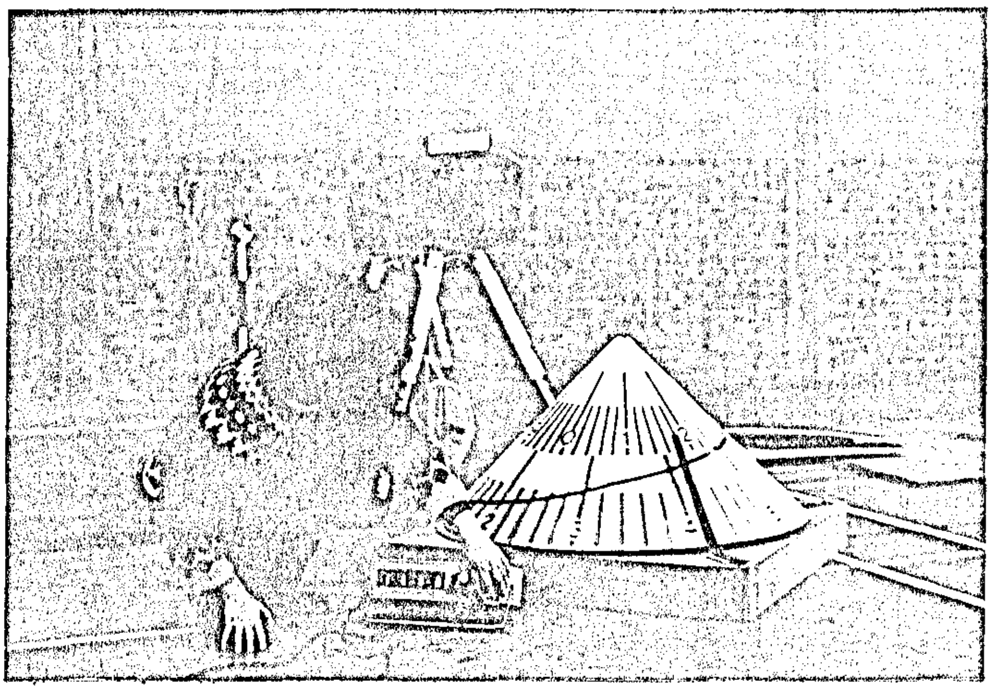


Figure 9. Calibration of the conical timer using the Venner electronic clock.

Table 1.

Duration of the contact phase read from the conical timer and the continuous motor clock.

Vault	Conical timer (ms)	Continuous motor clock (ms)	Vault	Conical timer (ms)	Continuous motor clock (ms)
HPTV	268	278	TSH	424	410
JTTV	188	179	AAH	258	253
JBTV	184	191	DMH	294	287
TSTV	270	269	HPY	204	199
AATV	206	193	JTY	233	228
DMTV	204	191	JBY	227	213
HPH	434	427	TSY	300	292
JTH	286	282	AAY	262	255
JBH	225	214	JBHSF	197	204

conical timer was found to be $s_{meas} = 5.1ms$. This gives an error of 2.6% for the conical timer, which is considered to be acceptable. The results and line of best-fit have been plotted in Figure 10.

Force platforms and ancillary equipment

The force platforms, Wheatstone bridge circuit, amplifiers and the U-V recorder were calibrated as one unit, since they were connected and operated as one unit for Experiment 1.

The platforms were calibrated statically in both a pre-loaded and an unloaded condition. Loads ranging from 50 to 403.8lbs were first placed on the platform in a progressive series and readings taken. These readings were repeated during unloading to permit account to be taken of hysteris effects. In a second series, a pre-load of 100lbs was first added, the zero reset, then the loading and unloading conditions were combined and sequences repeated. The pre-loaded and unloaded results were used to produce a calibration factor for each component of the two platforms.

Vertical (z) axis

The amplifiers were set in the range used in the experiment and known weights were placed on the platform in ascending order and then removed one at a time in the reverse order. Thus each platform was calibrated in loading and unloading conditions. Two 50lb. weights were then placed on the platform, the zero reset and the procedure repeated. The resulting U-V records were measured using a standard metric drafting scale. Each was measured five times along different portions of the trace; the results are given in Table 2.

The mean for each of the five trials was calculated. A two-tailed

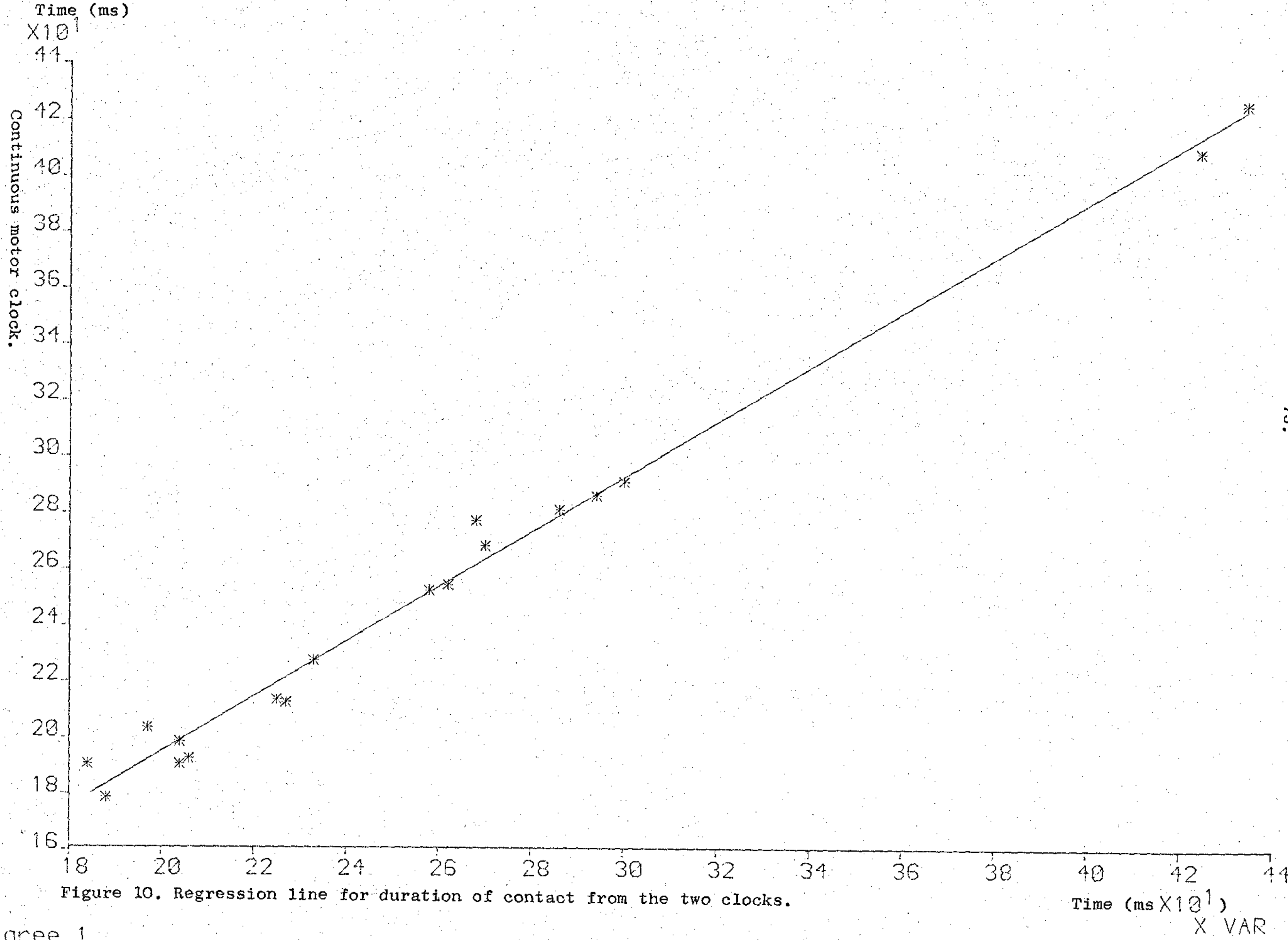


Figure 10. Regression line for duration of contact from the two clocks.

Degree 1

2

Table 2.

Table showing the galvanometer deflection (mm) measured five times for each applied load under various test conditions for the vertical component of both force platforms.

	Load (lbs.)	Condition *	Additional Platform Load (lbs.)	Galvanometer Deflection (mm)					
				1	2	7	4	5	Mean
PLATFORM 1	50	on	0	12.5	12.7	12.7	12.6	12.6	12.52
	50	off	0	12.5	12.5	12.4	12.3	12.3	12.4
	100	on	0	25.0	25.2	25.3	25.2	25.2	25.18
	100	off	0	25.0	25.0	25.0	25.0	25.0	25.0
	151.25	on	0	37.7	37.8	37.5	37.5	37.7	37.64
	151.25	off	0	37.7	37.8	37.7	37.5	37.7	37.58
	202.5	on	0	50.5	50.3	50.5	50.7	50.5	50.5
	202.5	off	0	50.5	50.5	50.4	50.5	50.7	50.52
	403.8	on	0	100.5	100.3	100.7	100.7	100.3	100.5
	102.5	on	100	25.5	25.5	25.5	24.5	25.5	25.48
	102.5	off	100	25.5	25.5	25.5	25.5	25.5	25.5
	303.8	on	100	75.5	75.5	75.5	75.5	75.5	75.5
PLATFORM 2	50	on	0	13.7	13.7	13.8	13.7	13.7	13.72
	50	off	0	11.9	12.0	11.8	11.9	11.8	11.88
	100	on	0	26.2	26.3	26.2	26.2	26.3	26.24
	100	off	0	25.2	25.3	25.2	25.3	25.1	25.22
	151.25	on	0	39.2	39.3	39.2	39.2	39.2	39.21
	151.25	off	0	39.0	39.0	38.8	38.7	38.9	38.88
	202.5	on	0	51.9	51.7	51.7	51.7	51.8	51.74
	202.5	off	0	52.0	52.0	52.0	52.0	52.0	52.0
	403.8	on	0	101.2	101.3	101.2	101.3	101.2	101.24
	201.96	on	100	51.5	51.6	51.7	51.8	51.7	51.66

*
on = load measured in the ascending order
off= load measured in the descending order

t-test of the differences of the paired observations (see page 102) for the loading and unloading situations was conducted, for both platforms. The results were not significantly different at $\alpha = 0.2$, showing that even at this low level of significance there was no difference between the means.

The line of best-fit through the calibration readings was calculated using the POLFIT program (page 102). This produced a calibration graph containing the points, the line and regression equation for the line. (Figures 11 and 12).

Horizontal (x) axis

A cable tensiometer exerting a measured force, horizontally, on each stationary platform, was used to calibrate the horizontal component.

One end of the tensiometer was firmly attached to the wall, the other to a frame on top of the force platform. The equipment had been designed to ensure the cable was horizontal and that the platform was stationary. See Figure 13.

Each platform was calibrated in the unloaded and pre-loaded (100lbs) condition. The tension in each case was increased progressively to 300lbs then decreased in similar steps.

Two-tailed t-tests were conducted as for the vertical axis and they also showed no difference between the means at $\alpha = 0.2$. Results are presented in Tables 3 and 4 and Figures 14 and 15.

The Haff planimeter

A reliability study was conducted on the integrating technique, using a Haff planimeter.

One force trace was integrated ten times resulting in a mean of

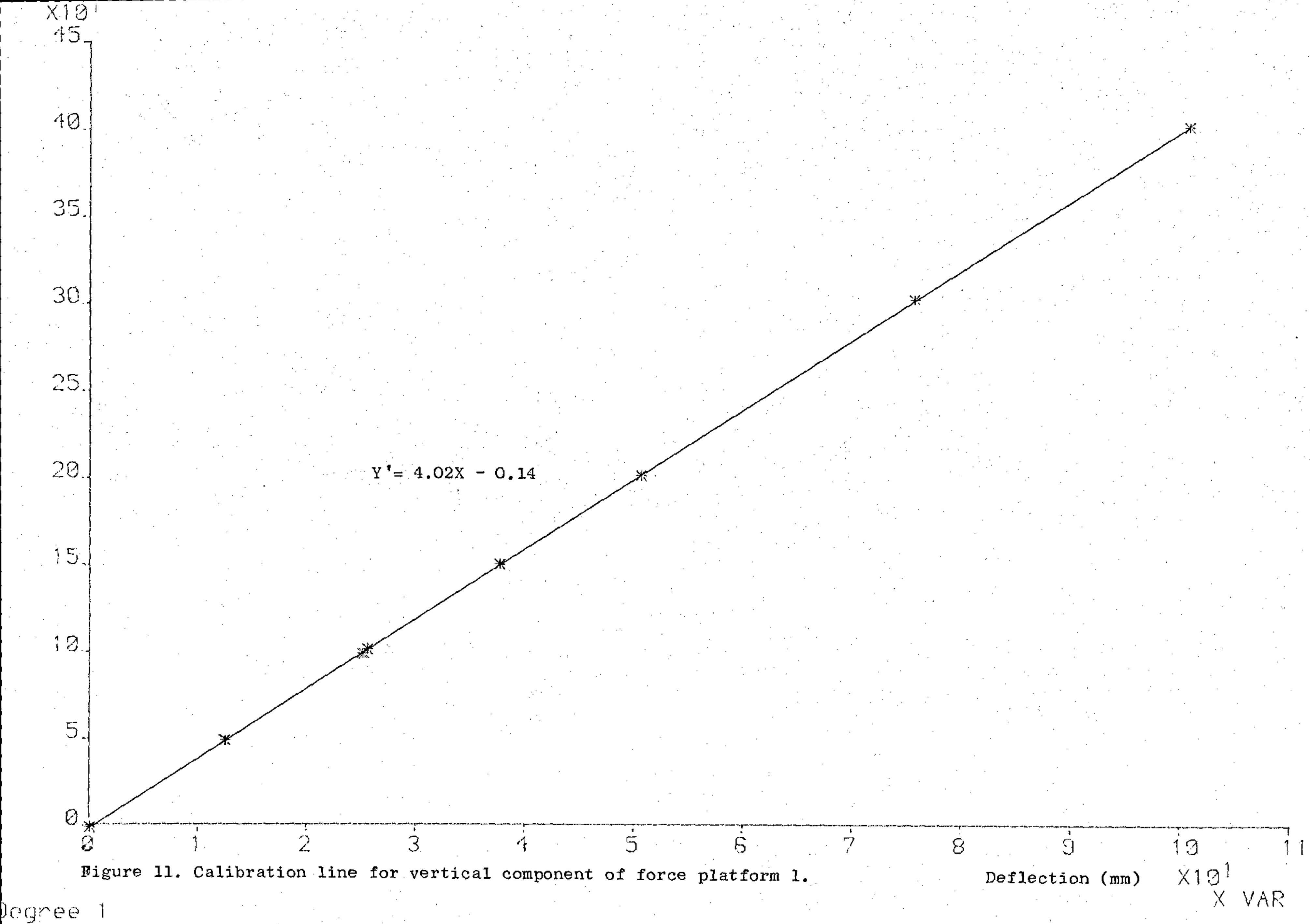


Figure 11. Calibration line for vertical component of force platform 1. Deflection (mm)

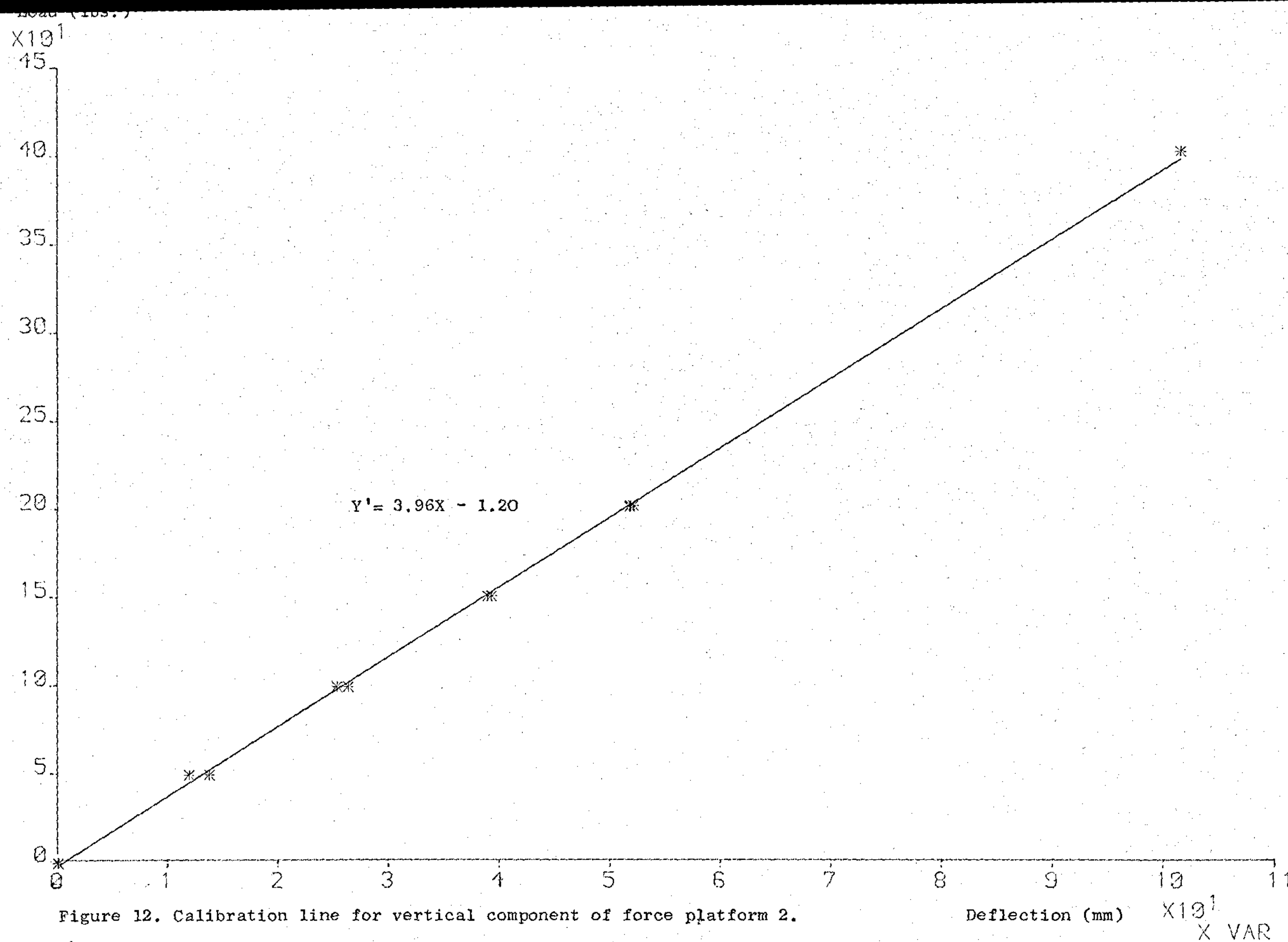


Figure 12. Calibration line for vertical component of force platform 2.

Degree 1

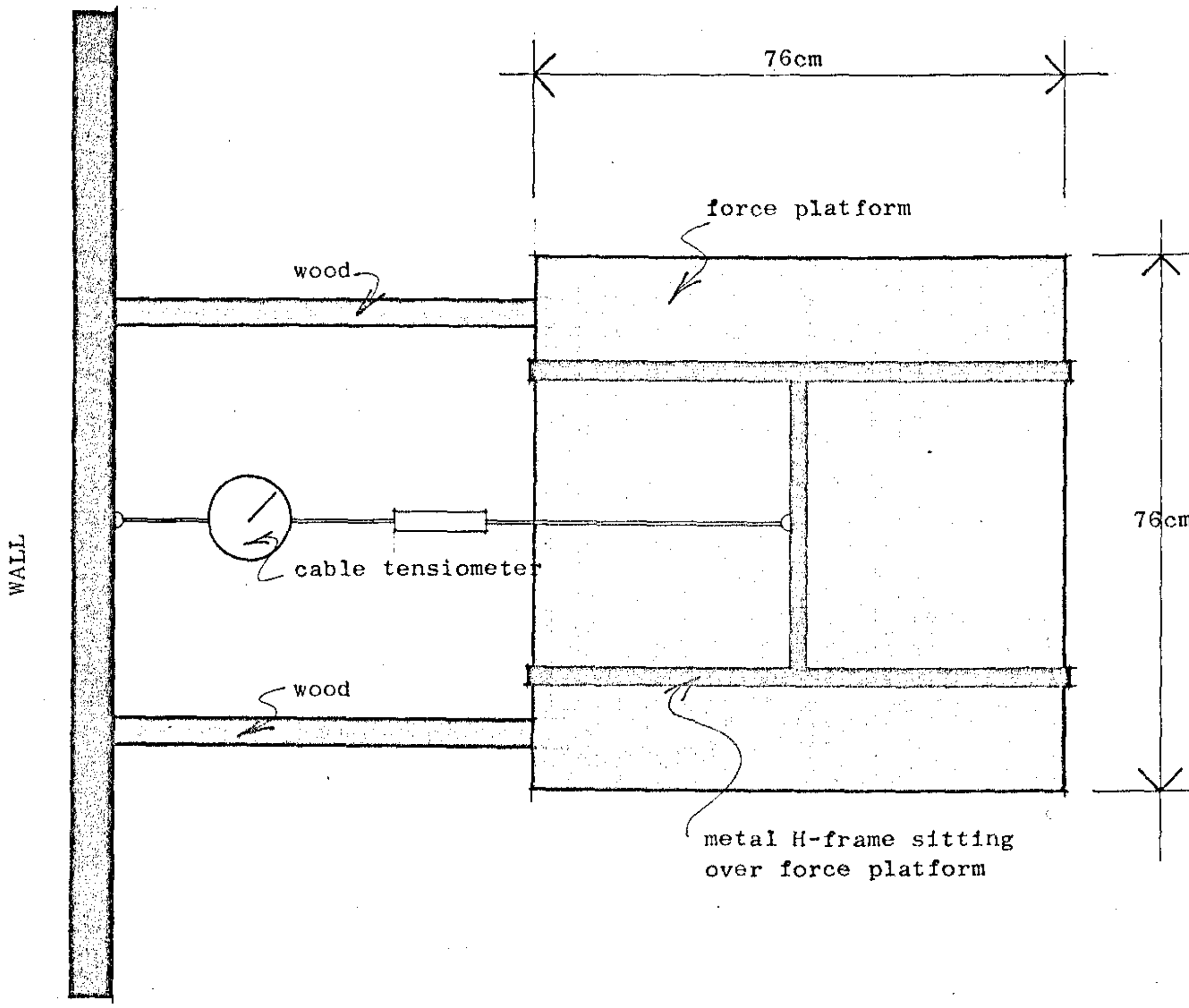


Figure 13. Diagram showing the arrangement used to calibrate the horizontal component of the force platform.

Table 3.

Table showing the galvanometer deflection (mm) measured five times for each applied load under various test conditions for the horizontal component of force platform 1.

Load (lbs.)	Condition	Additional Platform Load (lbs.)	Galvanometer Deflection (mm)					
			1	2	3	4	5	Mean
50	on	0	7.9	8.0	7.9	7.9	7.8	7.90
50	off	0	8.7	8.6	8.5	8.6	8.6	8.60
100	on	0	16.5	16.5	16.4	16.4	16.5	16.46
100	off	0	17.1	16.9	16.9	17.0	16.9	16.98
150	on	0	25.0	25.0	25.2	25.2	25.1	25.10
150	off	0	25.5	25.4	25.4	25.3	25.3	25.38
200	on	0	32.8	32.8	33.0	33.1	33.1	32.96
200	off	0	33.3	33.2	33.2	33.2	33.2	33.22
250	on	0	41.2	41.4	41.3	41.2	41.1	41.24
250	off	0	41.2	41.2	41.3	41.4	41.3	41.28
300	on	0	49.0	49.0	49.0	49.0	49.0	49.0
50	on	100	8.4	8.5	8.5	8.5	8.5	8.48
50	off	100	8.5	8.4	8.0	8.1	8.0	8.20
100	on	100	16.7	16.7	16.6	16.5	16.6	16.62
100	off	100	16.3	16.4	16.4	16.3	16.3	16.36
150	on	100	24.8	24.8	24.8	24.8	24.8	24.80
150	off	100	24.7	24.5	24.6	24.7	24.6	24.62
200	on	100	32.9	32.9	33.0	33.0	33.0	32.94
200	off	100	32.8	32.8	32.9	32.9	32.9	32.86
250	on	100	41.3	41.2	41.2	41.3	41.3	41.26
250	off	100	41.2	41.2	41.2	41.2	41.2	41.20
300	on	100	49.5	49.7	49.7	49.8	49.8	49.7

Table 4.

Table showing the galvanometer deflection (mm) measured five times for each applied load under various test conditions for the horizontal component of force platform 2.

Load (lbs.)	Condition	Additional Platform Load (lbs.)	Galvanometer Deflection (mm)					
			1	2	3	4	5	Mean
50	on	0	7.3	7.4	7.4	7.3	7.3	7.32
50	off	0	7.4	7.3	7.3	7.4	7.4	7.36
100	on	0	14.8	14.8	14.8	14.8	15.0	14.84
100	off	0	14.8	14.9	14.8	14.9	14.8	14.84
150	on	0	21.8	21.8	21.8	21.9	21.9	21.84
150	off	0	22.0	21.9	22.1	22.0	22.0	22.00
200	on	0	29.4	29.0	29.0	29.0	29.0	29.08
200	off	0	29.5	29.4	29.5	29.4	29.4	29.44
250	on	0	36.3	36.3	36.2	36.5	36.4	36.34
250	off	0	36.7	36.8	36.8	36.8	36.8	36.78
300	on	0	44.0	43.9	44.0	44.0	44.0	43.98
100	on	100	14.5	14.5	14.4	14.5	14.4	14.48
100	off	100	14.4	14.5	14.6	14.5	14.5	14.50
200	on	100	29.0	29.0	29.0	29.0	29.0	29.00
200	off	100	29.0	29.0	29.0	29.0	29.0	29.00
300	on	100	43.8	43.7	43.7	43.7	43.7	43.72

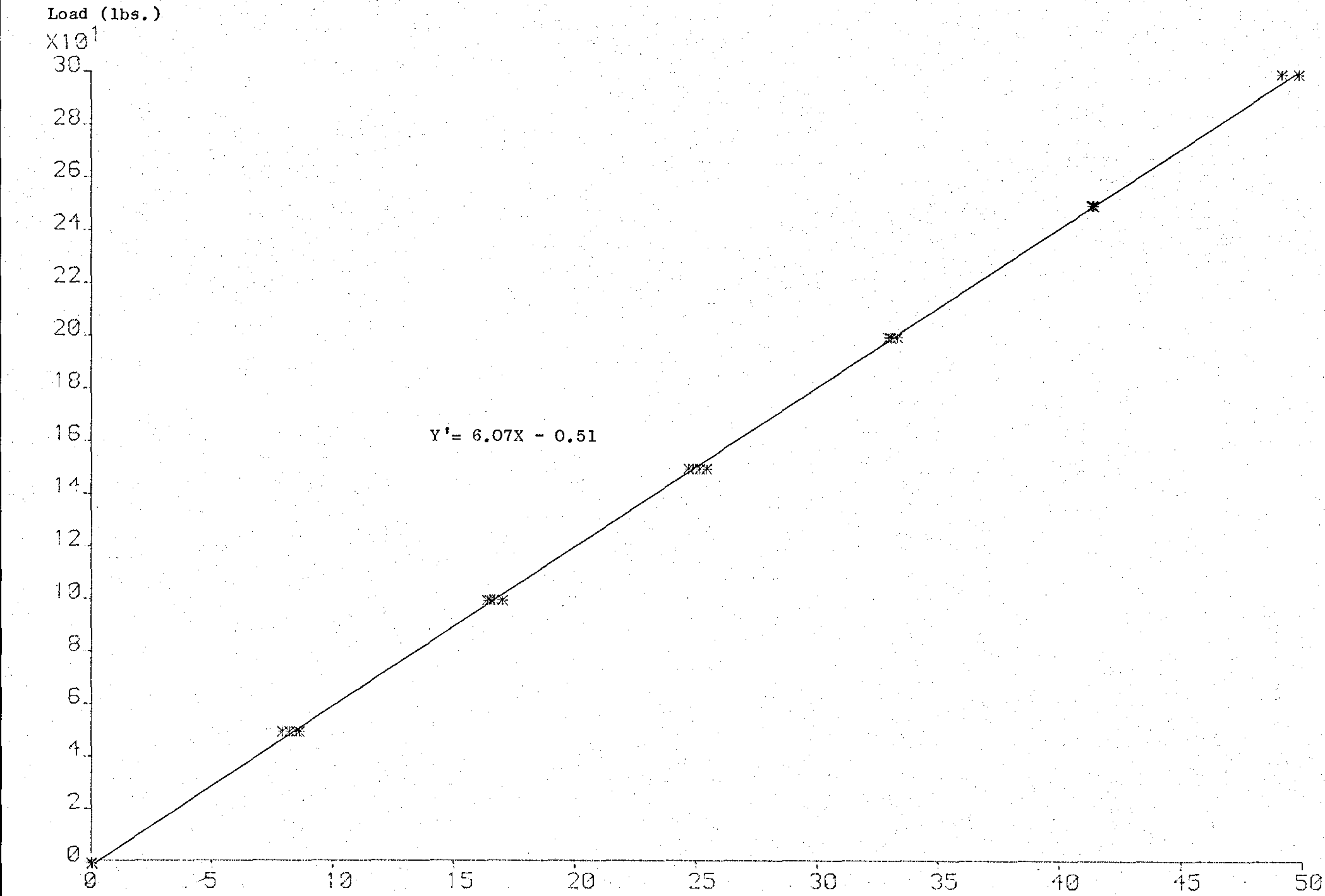


Figure 14. Calibration line for horizontal component of force platform 1.

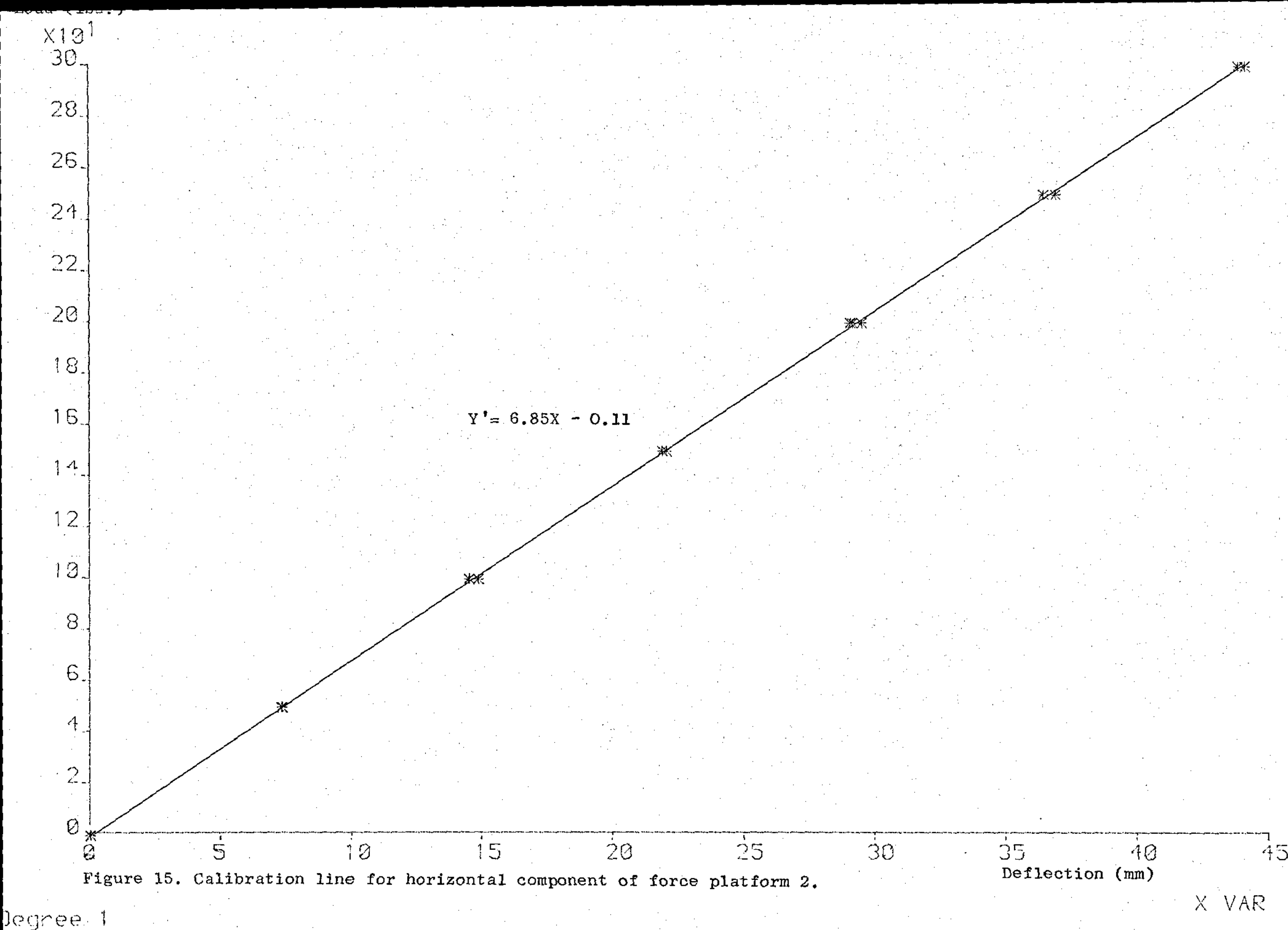


Figure 15. Calibration line for horizontal component of force platform 2.

$7.7cm^2$ and a range of $7.5 - 7.9cm^2$. This giving a standard deviation of $0.12cm^2$, and an error of 1.6%, is considered to be acceptable and indicates that this was a reliable method.

The Vanguard analyser

Scale correction

The distances measured from the film were scaled to half life size using a metre scale filmed in the object plane. The ratio of the actual size of this scale to the measured size of the image was set using potentiometers on the Vanguard analyser.

Initially the zero position was set in the corner of the scale, then the one metre length of the horizontal arm was set equal to 500mV. A similar procedure was followed for the vertical arm. The zero was then shifted to an arbitrary position in the lower left-hand corner of the screen and the one metre lengths measured again. An error of less than 3mV equivalent to 6mm in real distance was acceptable.

Digitising technique

The reliability of the equipment and the author's digitising technique were tested in conjunction with the centre of gravity program (COFG, Appendix E). Ten frames of the same vault were digitised on two occasions. The raw data were processed in the manner adopted for this study (see page 94) and the position of the subject's centre of gravity in each frame was calculated. No effort was made to standardise the location of zero for the two occasions, instead the mean difference between the two sets of data was calculated and then each value in the second set was corrected for the systematic error. The corrected data are presented in Table 5.

Table 5.

Horizontal and vertical displacement data for the same vault digitised twice.

Horizontal		Vertical	
1	2	1	2
1.383	1.389	1.646	1.654
1.444	1.450	1.702	1.706
1.505	1.505	1.755	1.756
1.567	1.560	1.799	1.805
1.624	1.618	1.849	1.850
1.683	1.679	1.897	1.893
1.737	1.739	1.941	1.934
1.799	1.800	1.979	1.977
1.858	1.857	2.024	2.018
1.920	1.921	2.055	2.049

A regression analysis was then conducted, the second set of values being regressed on the first. The standard error of the regression estimate was determined. It was observed that the β coefficient was approximately unity ($\beta_{y.x} = 0.994$ horizontal data and $\beta_{y.x} = 0.968$ vertical data).

The regression line is shown plotted against the horizontal and vertical data in Figures 16 and 18.

The standard error of the estimate is quite small e.g. it is $s_e = 0.0046$ horizontally and $s_e = 0.0031$ vertically and can be seen to be random from the graphs of the residuals in Figures 17 and 19.

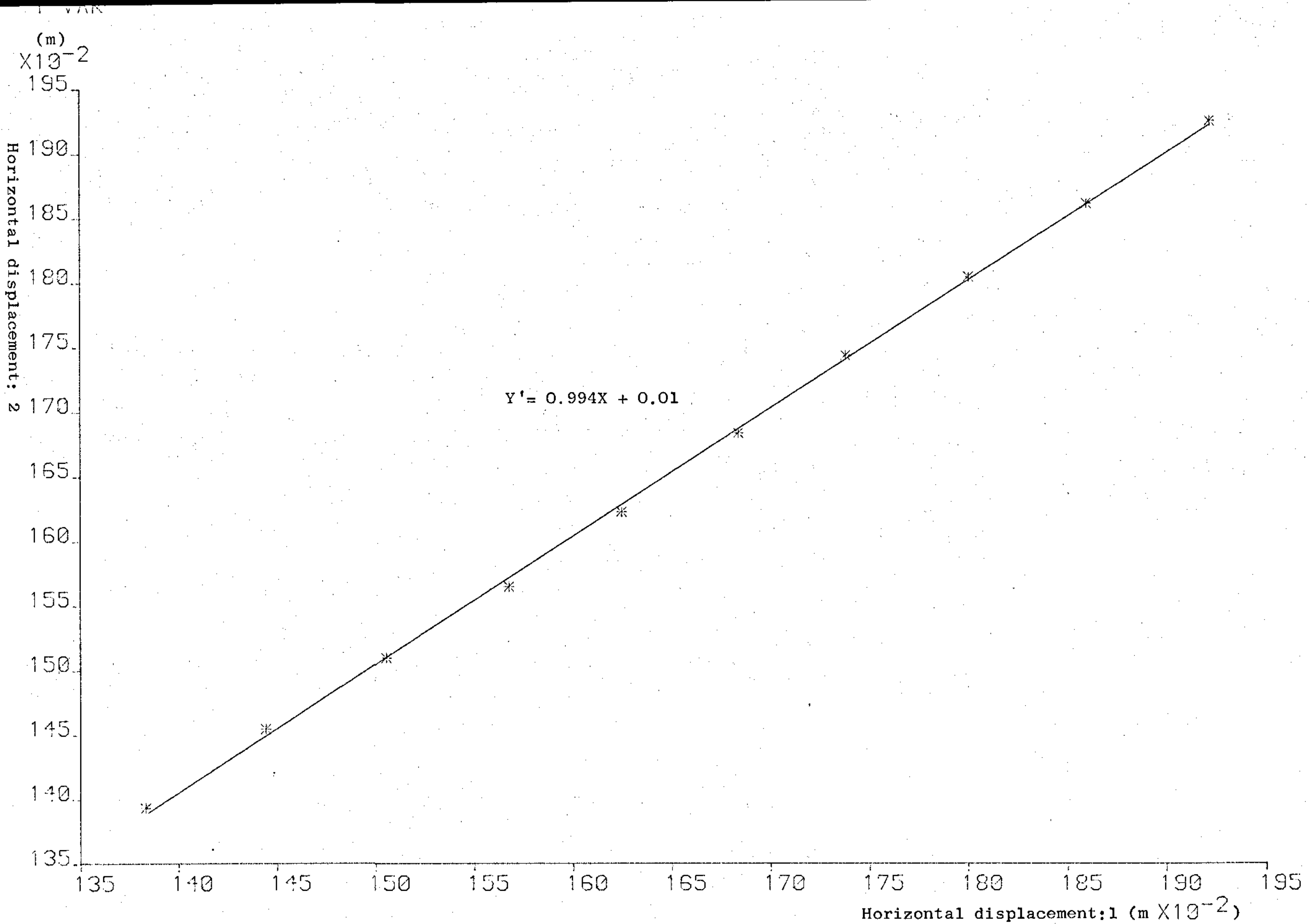


Figure 16. Regression line for horizontal displacement data.

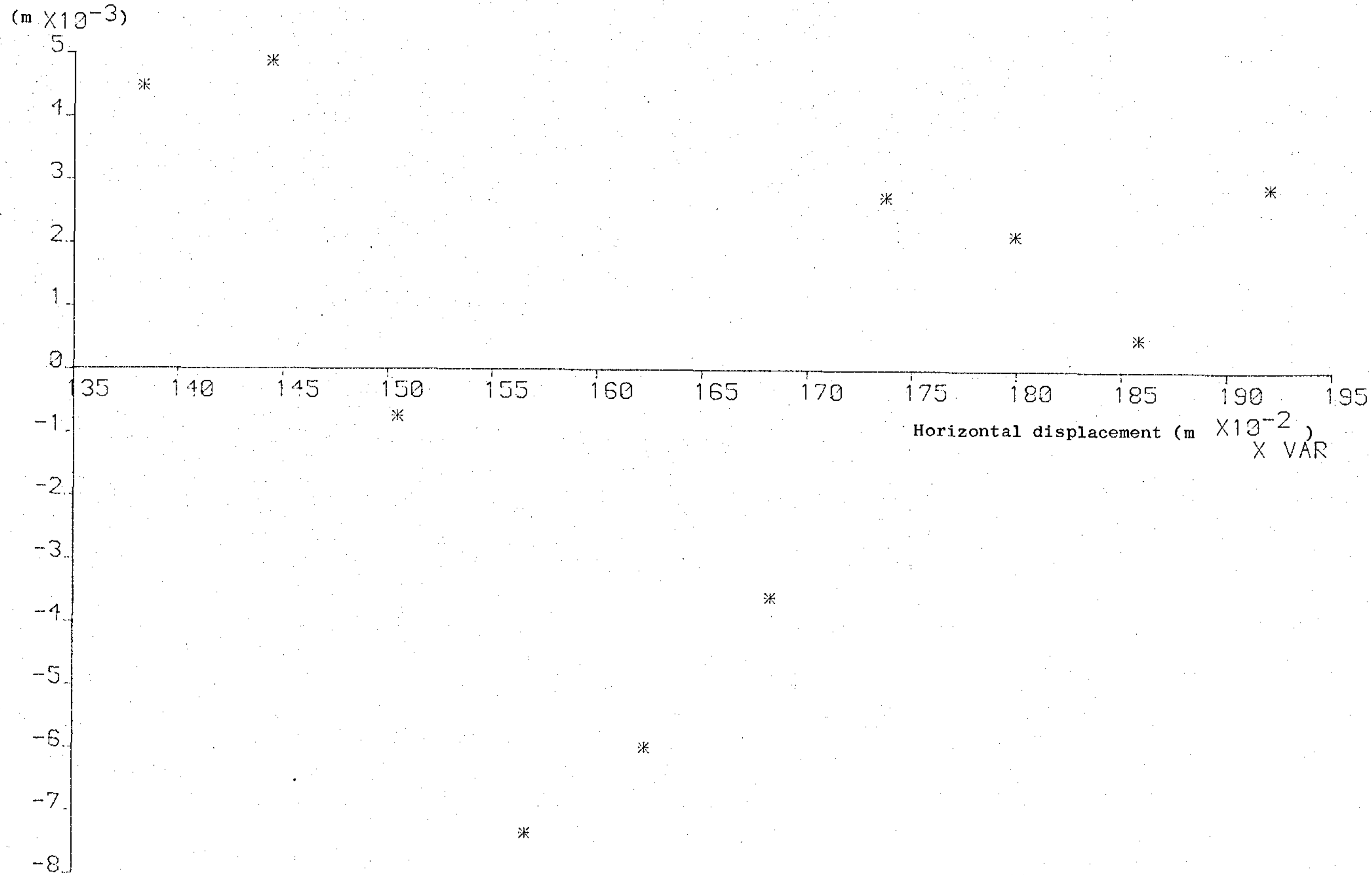


Figure 17. Graph of residuals for horizontal displacement data.

Degree 1

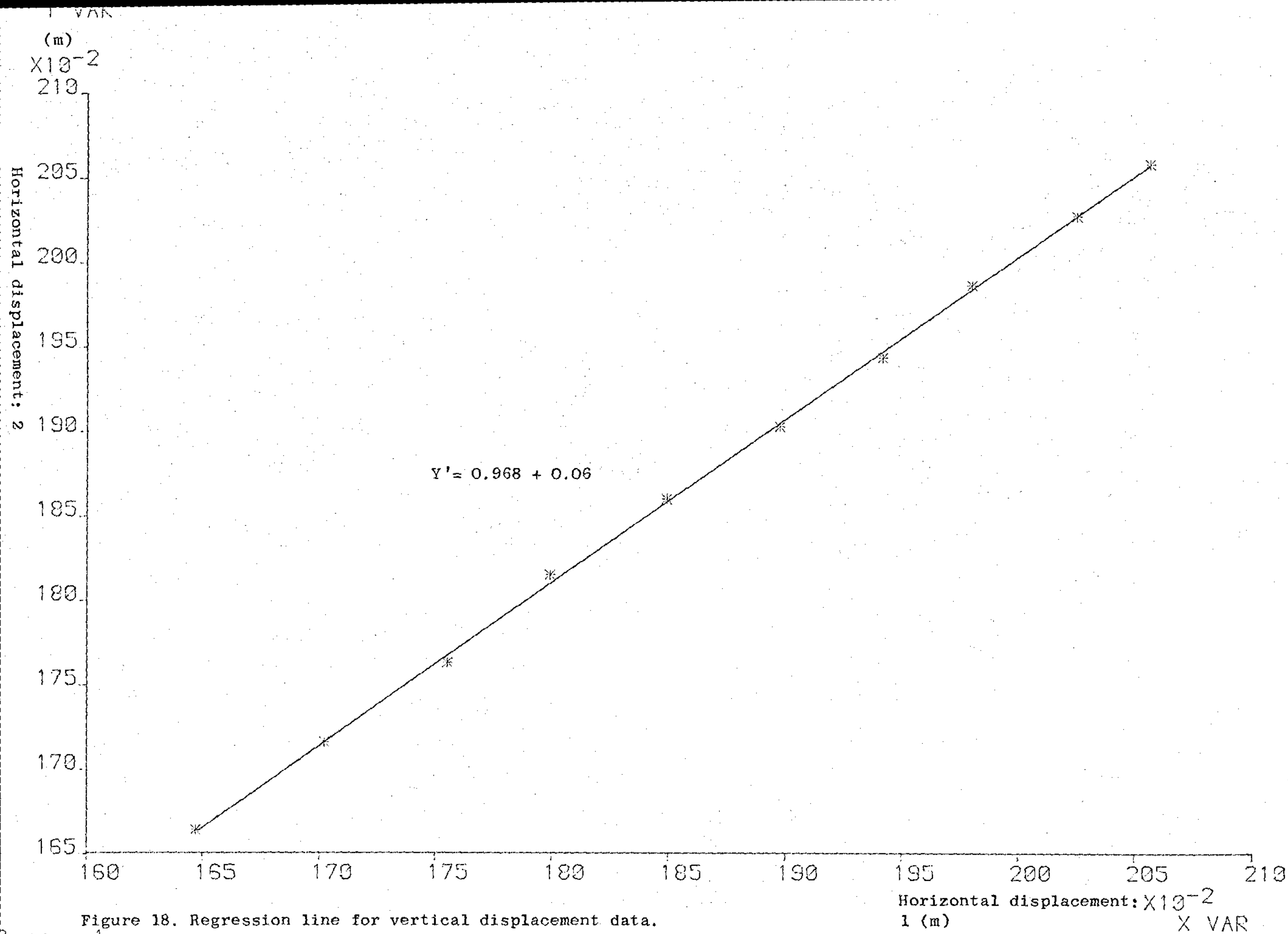


Figure 18. Regression line for vertical displacement data.

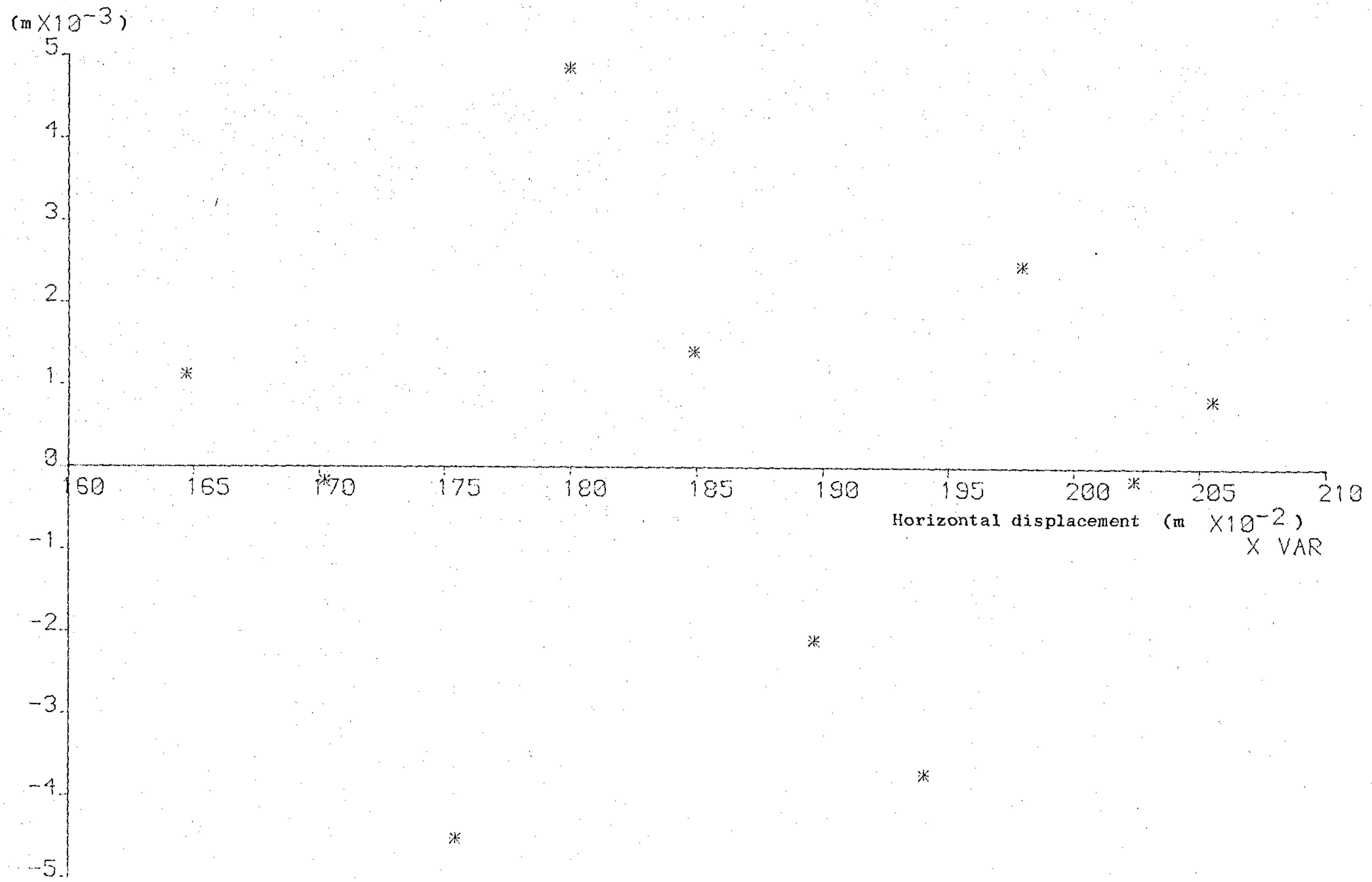


Figure 19. Graph of residuals for vertical displacement data.

Degree 1

This random error then is the magnitude of error to be expected from the data transcription process.

Validity of the cubic spline fit to parabolic data

A vault, from take-off to landing, consists basically of two parabolae with an intervening phase of rapid acceleration. Other researchers (McLaughlin et al, 1977) have not had good results when using the cubic spline to smooth and double differentiate parabolic displacement data, especially at the end points.

However, they used Reinsch's algorithm (1967) which has as a feature the end conditions of

$$s''(0) = t(max) = 0$$

where s'' is the value of the second derivative of the spline. The use of this algorithm does produce valid readings near the endpoints in parabolic motion.

The spline used in this study is based on Cox's algorithm (1975) which differs from Reinsch's in that the end conditions of the second derivative are not fixed. The technique uses B-splines or fundamental splines as a basis function. These splines are fitted over four knots and summed to produce values at the knots which define the cubic functions. This necessitates the addition of four extra knots placed at each end, which allow the conditions of the function at the end conditions to be met accurately.

The validity of Cox's algorithm was evaluated on theoretical data for parabolic motion. The following graphs have been plotted against time: vertical displacement, Figure 20, the residuals, Figure 21, vertical velocity, Figure 22 and vertical acceleration, Figure 23. The residuals are of a very small order, and reflect the rounding to two

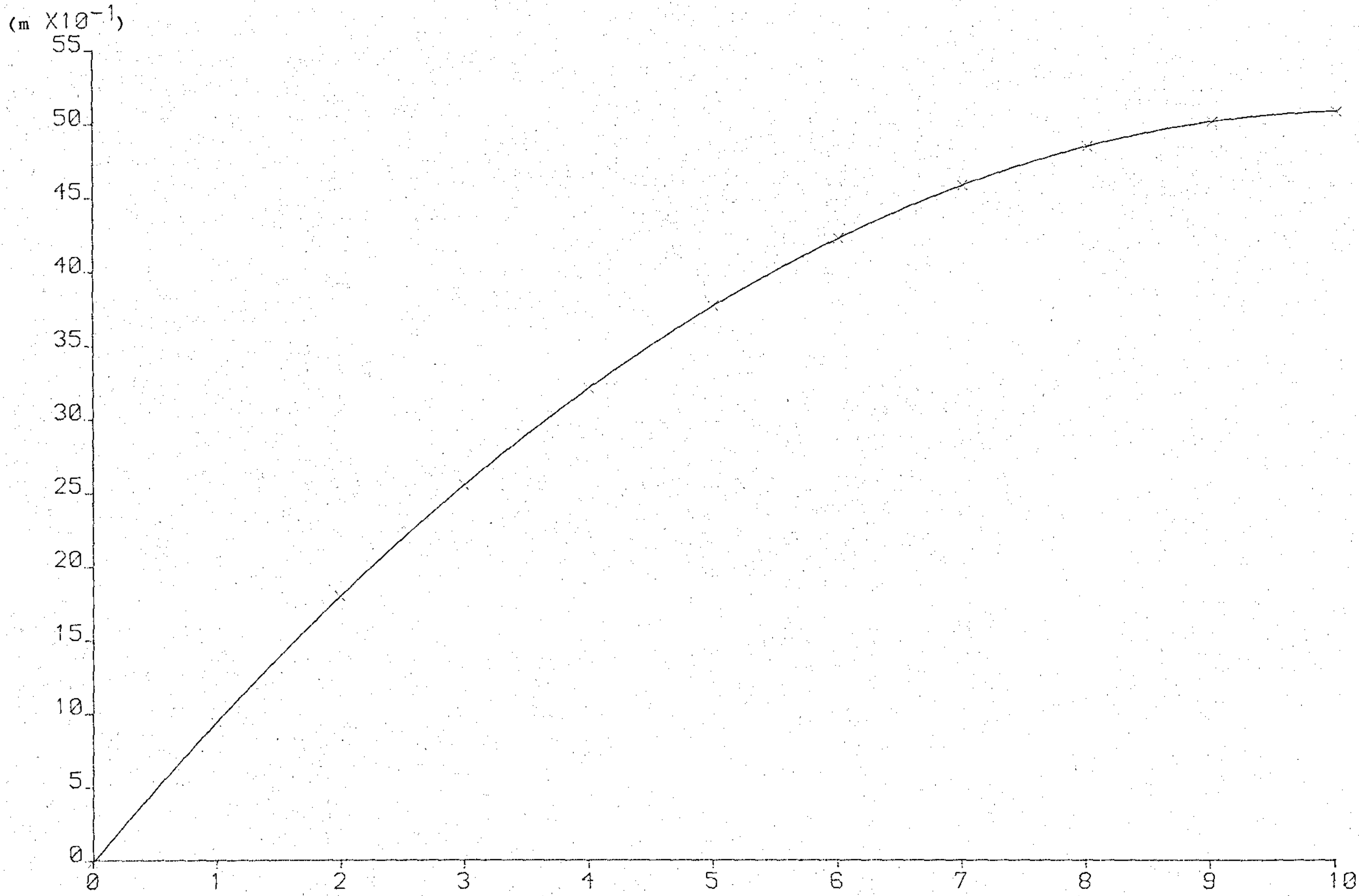


Figure 20. Cubic spline fit to parabolic data.

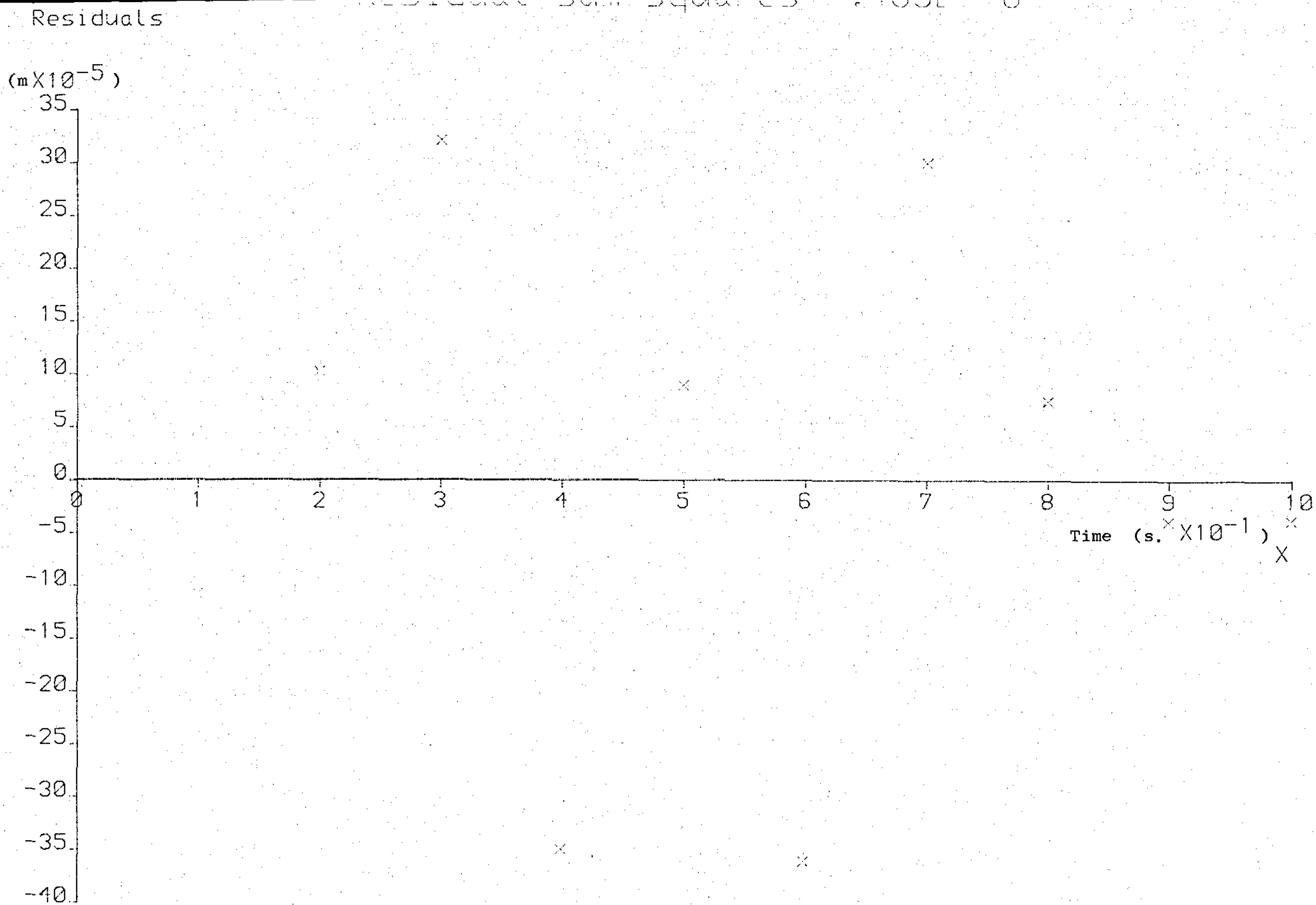


Figure 21. Residuals.

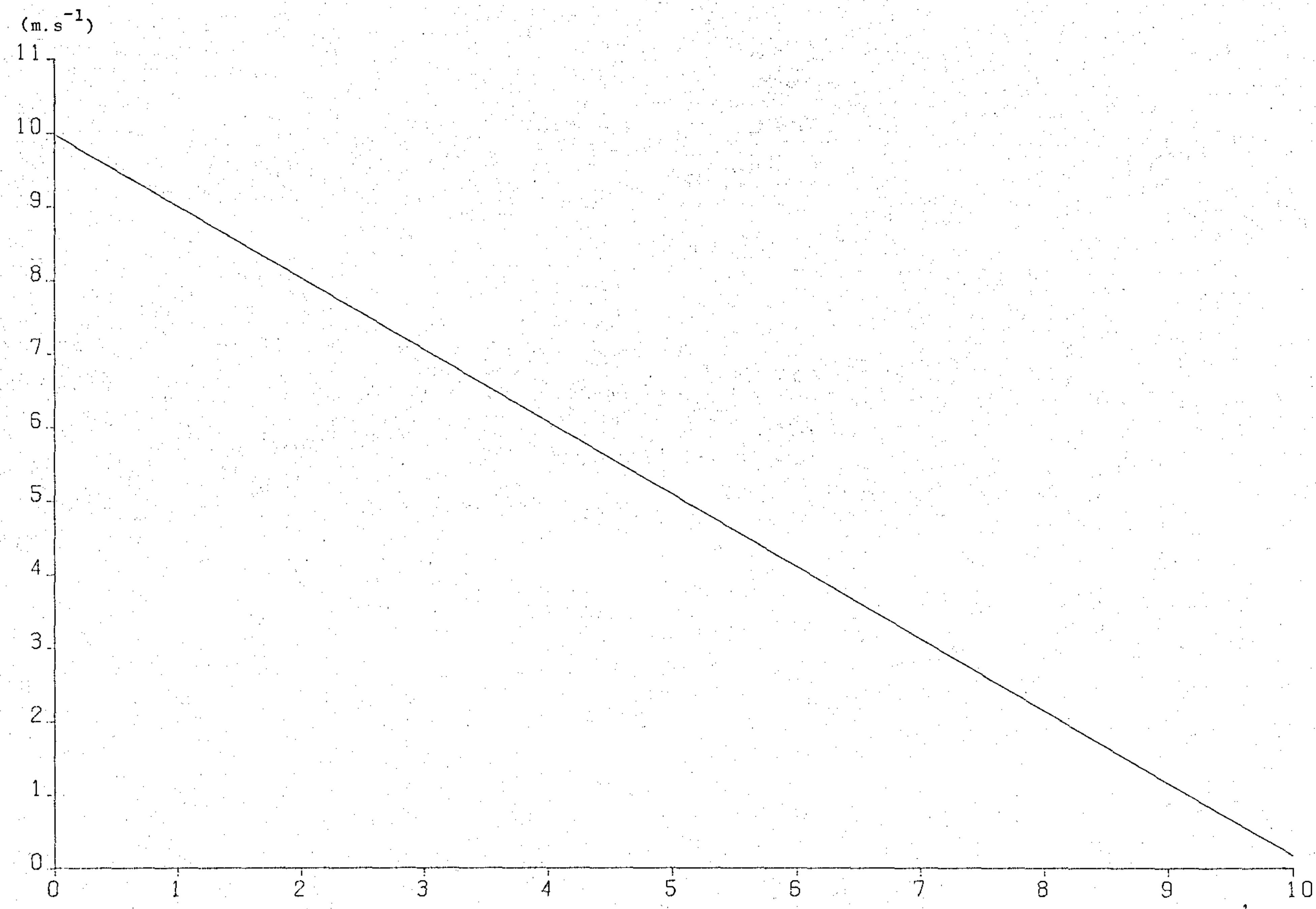


Figure 22. Vertical velocity.

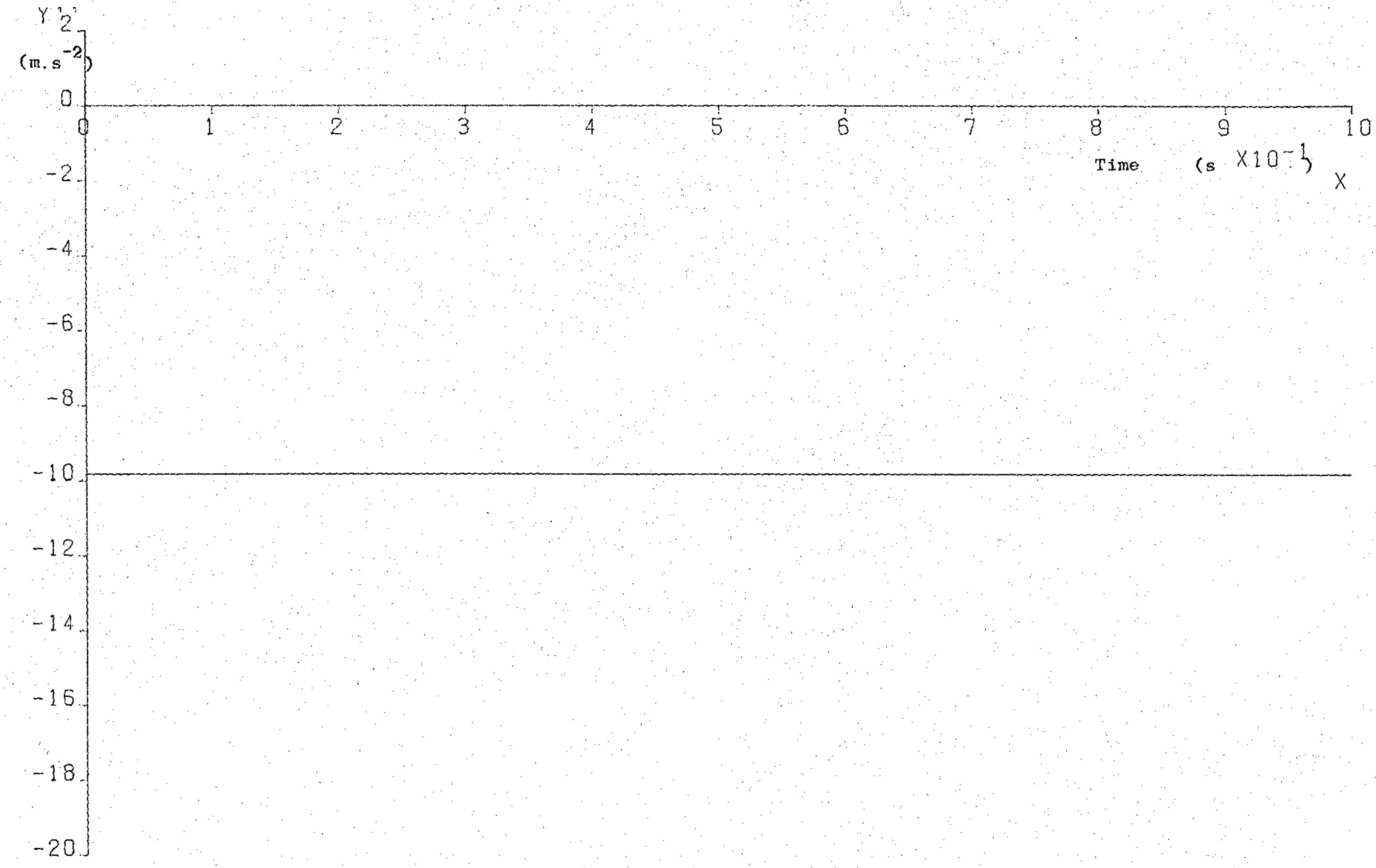


Figure 23. Vertical acceleration.

decimal places of the input data, the velocity graph appears to be linear. From Figure 23 it can be seen that the acceleration has a constant value of $-9.8 m.s^{-2}$ as would be expected. Hence the velocity graph is not only linear but also has the required slope. The cubic spline based on Cox's algorithm was considered to give a valid representation of the data and its derivatives for parabolic motion.

ANALYSIS OF DATA

Raw data

The raw data was initially inspected using the Sigma terminal and the program PLOTVAULT (see Appendix E). This inspection revealed any errors in the sequence of digitising the eleven points for each frame. The program enabled the user to inspect every seventh frame of the vault and notice any discrepancies in the configuration of the performer.

On several occasions the upper arm had not been digitised, so these frames were deleted. Inspection also revealed that occasionally the same point had been digitised twice so one of these points was edited from the file.

Duration of the phases

The error in measuring the duration of the phases will be compounded by not knowing the exact time of contact or take-off.

The conical timer was read for the following frames:

1. First frame of pre-flight
2. First frame of horse-contact
3. First frame of post-flight
4. Last frame of post-flight

From these readings the average time interval between frames was calculated for the different phases:

T1: duration of pre-flight. This was calculated between the first frame of pre-flight to the mid-point between the last frame of pre-flight and the first of contact. Since the gymnast may have left the board up to 16ms before the frame taken as the first frame of pre-flight, this error must be taken into account. Similarly there could be a 8ms error in the time of contact. In all a possible total of 24ms in an average pre-flight time of 311ms, giving a maximum error of 7.7%.

T2: duration of contact. Since the times of contacting and leaving the horse were taken at the mid-points of successive frames where contact was seen to be made or lost there is a total maximum error of 14ms in T2; giving for the average value of T2, 297ms, an error of 4.7%.

T3: duration of post-flight. This was taken from loss of contact with the horse, as above, until the last frame of post-flight, hence it has a 24ms error: giving a 4.7% error for the average of 509ms.

For the above reasons the duration of the different phases is given to two decimal places.

<u>Calculation of centre of gravity</u>

The program COFG (see Appendix E) was used to calculate the centre of gravity of the body for each frame. This program uses the segmental method based on a nine segment model and required eleven points to be digitised for each calculation.

Data from Cook's (1978) study on female gymnasts was used for the percentage mass of the different segments. Cook used the water tank displacement method as described by Dempster (1955) to calculate the mass of the various segments for six gymnasts. She also used the density values given by Dempster.

Kjeldsen (1969) performed the same experiment on six gymnasts, however her results indicate that the subjects were more 'pear' shaped, since she had a large value (34.2%) for the abdomen and pelvis. The gymnasts in this present study tended to have broad shoulders and a narrow pelvis therefore it was décided to use Cook's data.

The percentage distances of the segmental centre of gravity from the proximal joint centre used in this program were from Johnson's study (1976) and Dempster's study (1955) for the torso segments. The data concerning the segments is given below in Table 6.

Table 6.

Segmental data

Segment	% segmental mass	% distance from proximal joint to centre of gravity
Head	11.6	43.3
Thorax	18.6	62.7
Abdomen and pelvis	17.0	59.9
Thigh	29.9	44.5
Leg	9.4	45.8
Foot	3.1	46.8
Upper arm	6.5	47.6
Forearm	2.9	48.4
Hand	1.1	49.3

The moments for the segments were summed about the origin and the centre of gravity for each frame was calculated. The output from this program was in the form of a hard-copy giving the position of the X and Y coordinates and the time for each frame. These are presented in Appendix B.

Files were also created for later use. These files included: the X and Y displacements for plotting the path of the centre of gravity; time and horizontal displacement for calculating the horizontal velocity; time and vertical displacement for calculating vertical velocity.

Calculation of change in displacement

For the pre-flight and contact phases of the vault the changes in displacement were calculated by subtracting the initial value for that phase from the initial value of the next phase.

Vertical displacement during contact was calculated to have the smallest of these four values ($\overline{Z2} = 0.24$m). Since the expected error in each displacement point is 3mm the resulting error in this calculation is 2.5%.

However for post-flight vertical displacement the percentage error using this technique would be much greater since the value is generally less, ZFL ranges from -0.01 - 0.23m. Hence when calculating the difference between the peak of the second parabola and the position at loss of contact, the results read from the Tables in Appendix B were compared to results read from the smoothed displacement time graph. Where these did not agree to the nearest centimetre the value read from the graph was taken to be correct.

The change in horizontal displacement was calculated from the last frame of contact until the last frame of post-flight.

Calculation of the performance criterion score

The performance criterion score is the sum of the standardised scores for the horizontal (XFL) and vertical (ZFL) displacements of post-flight. A series of standardised scores was calculated for each vault from the values of the subjects in Experiment 1. The performance criterion score for each performer was calculated from the equations:

$$ZXFL = (XFL - MEAN(XFL)) / SQRT (VAR(XFL))$$

$$ZZFL = (XFL - MEAN(ZFL)) / SQRT (VAR(ZFL))$$

$$Z = ZXFL + ZZFL$$

These calculations were included in the GENSTAT package.

Smoothing the displacement-time data

Horizontal data

The file created by the program COFG containing the horizontal displacement and time data was used to calculate the horizontal velocity over the free-flight phases.

This file was initially edited and two files were created. The first contained all the points for pre-flight and no points where the gymnast was in contact with the apparatus. The second similarly contained all the points of post-flight. These files were each read into the POLFIT.DIALOG program which is available at Loughborough University through the computer centre. A polynomial of degree one was selected and fitted to each set of data. The resulting equation for the line was outputted from the program and the horizontal velocity taken from the value indicating the slope of the line.

Vertical data

The cubic spline technique was used to smooth the vertical displacement-time data. The package SFIT.DIALOG, again made available by the computer centre at Loughborough University, is an interactive program allowing the user to observe the plotted data and insert the knots accordingly.

Of all the terminals available, the Sigma S5660 provided the largest and most accurate picture, this terminal was therefore used in this process.

A knot was fitted at the begining of contact in between the points which indicate the last frame of pre-flight and the first frame of contact. The same procedure was used to place a knot at the end of contact.

A double knot, giving a discontinuous acceleration curve, was placed where the path of the centre of gravity was determined to be changing rapidly; i.e. at the end of the first parabola, where a marked upward displacement is shown. This position corresponds to the end of the compressive phase where there is a marked drop in acceleration, hence the inclusion of the double knot was justified. A fourth knot was placed mid-way between the double knot and the end of contact.

The location of the knots in these positions produced the best results minimising the magnitude and maximising the randomisation of the residuals and giving accurate values for g in the free-flight phases.

The program enabled the production of graphs using the CALCOMP plotter. The vertical velocity graphs were used to determine the take-off, contact and initial post-flight vertical velocities for all performances.

Angular kinematics

The body angles at take-off and contact were calculated by plotting the coordinates of the feet and the centre of gravity for the first frame each of pre-flight and contact. These two points were joined by a line and the angle measured to the right horizontal. The error involved in this technique is small since the angles are large and a 3mm error in the location of both points over a length of one metre would give an error of 0.34 degrees.

The angular velocity calculations were "smoothed" by the process of calculating this value over seven frames. These frames were the first seven frames of pre-flight drawn using the PLOTVAULT program.

A line was drawn on each of the figures, between the knee and the C7-T1 intersection. The angle between these lines was measured and divided by the time interval over the frames to produce the angular velocity value.

Impulse and force

Due to the low frequency oscillations produced by the horse on the force platforms, absolute force values could not be read from the traces.

These traces were integrated, using a Haff planimeter, to remove the effect of the oscillations. The oscillations of the horse were caused by the initial impact between the gymnast and the horse, therefore this initial peak value was considered to be true signal, and the initial trough considered to contain noise. Thus the traces were integrated from instant of contact until the end of the first peak after the gymnast had left the horse. The integral of the subsequent oscillations was zero.

The phases of compression and repulsion were also integrated, where compression ends and repulsion starts at the minimum point of the first major trough (generally below zero).

The addition of the impulses for compression and repulsion gave the same value as the total impulse. These impulses were then corrected to scale using the calibration factors presented in Figures 11 to 15 and the time interval over which the integration was conducted.

The values were converted to Newton.seconds. The impulses for the compression and repulsion phases were divided by the time interval of the phase and body weight, to express the average forces in terms of percentage body mass.

The total impulse was divided by body mass.

Statistical analyses.

Descriptive statistics

The Pearson product-moment correlation coefficient

The correlation coefficient between two sets was calculated using the raw score formula:

$$r_{xy} = \frac{n\sum_{i=1}^{n} X_i Y_i - (\sum_{i=1}^{n} X_i)(\sum_{i=1}^{n} Y_i)}{\sqrt{(n\sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2)(n\sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Y_i)^2)}}$$

Linear regression

The computer package POLFIT.DIALOG was used to calculate the line of best fit between two sets of variables. It also produced the standard error of the estimate.

Inferential statistics.

Related t-test.

This was used in comparing results obtained on the same variable, measured using different techniques.

$$t = \frac{\sum_{i=1}^{n} d_i / n}{\sqrt{\dfrac{\sum_{i=1}^{n}(d_i - \bar{d})^2}{n(n-1)}}}$$

with (n - 1) degrees of freedom, where n=number of pairs.

d_i = difference between paired observations (taking into account the difference of the sign).

$\bar{d}$ = mean of the differences.

GENSTAT statistical package.

The GENSTAT package was used to compute a sequence of three multi-linear regression equations in a stepwise manner. At each step one variable is added to the regression equation, the variable added is the one which makes the greatest reduction in the error sum of squares.

The f-ratio was calculated from the mean square results, using the following formula:

$$F = \frac{MS_b}{MS_w}$$

The GENSTAT package was also used to perform a one-way Analysis of Variance.

The standard measurement of the error was calculated:

$$s_{meas} = s_e / \sqrt{2}$$

CHAPTER 4

ANALYSIS OF RESULTS

OVERVIEW

The results of the experimental program are presented in three stages. In the first stage the nature of the sample is described and shown to be not unusual for highly skilled gymnasts.

In the second stage, initially the results of the first experiment are presented and the three vaults are described in biomechanical terms. The apparent dependence of the critical post-flight phase upon the initial phase of the vault is examined. Later, the results from the second experiment are used to validate the relationships shown between the three phases of the vault.

The third stage uses the results from Experiment 1 to determine the principal components which show pattern of change across the initial phases of the related vaults.

PART 1

Sample characteristics

The characteristics of the female gymnasts who participated in this study are summarized briefly in Table 7 , full details are available in Appendix F.

Table 7.

Sample characteristics

Number of subjects = 9

Experiment 1 (outside) = 6

Experiment 2 (indoors) = 3 (+1)

Skill level of subjects

International = 4

National = 3

Regional = 2

Physique

	Mean (S.D.)	Range	U.S.A. female gymnasts Mean (S.D.)
Height (cm)	158.4 (6.8)	148.0 - 167.7	160.6 (4.36)
Weight (kg)	51.1 (7.1)	37.5 - 59.5	53.7 (5.86)
Age (years)	17 (2.0)	14 - 21	19.4 (1.07)

Examination of the above summary table indicates that the physique characteristics are not unlike those shown by U.S.A. female gymnasts. Sinning (1978) found that U.S.A. gymnasts were shorter in height, lower in weight and had a higher body density than other college women. While no attempt has been made to estimate body density the results in this study, for the English gymnasts, show that the two groups have very similar anthropometric characteristics, and encourages the view that the English group was not in any way unusual in its physical characteristics.

PART 2

Before the results can be analysed certain tests must be made of the validity and accuracy of the data. While all care has been taken in deriving these results, certain procedures are prone to error, especially velocity calculations (Smith, 1975; Lees,1980).

Equations of parabolic motion lend themselves as useful methods with which to test the validity of the derived linear velocity results.

Validation of linear velocity calculations

Both the horizontal and vertical displacements were smoothed using polynomial smoothing techniques.

Initially an attempt was made to use the cubic spline for error reduction in both sets of data, since the spline will provide information concerning velocity for all phases of the vault. However for the free-flight phases of the horizontal displacement this technique did not produce constant horizontal velocity and the percentage error was greater than 5%. Therefore it was decided to fit a polynomial of degree one to the flight phases and ignore the changes in horizontal velocity that occur during contact.

However the cubic spline was found to produce good results for the vertical velocity. Results for subjects from both experiments were used in this validation.

Polynomial of degree one

In order to validate the horizontal velocity calculated using the polynomial smoothing technique, the duration of pre-flight (T1) was calculated from the equation

$s = vt$

where s = horizontal displacement between the first and last frames of pre-flight and has a possible error of 1%,

v = horizontal velocity calculated from smoothed displacement data.

The time calculated from this equation was then compared to the duration of pre-flight as read from the conical timer. As mentioned previously (page 94) value for duration of pre-flight has had 8ms added to it to reduce the percentage error variation of this variable. Therefore the calculated time should have a value of 8ms less than the read time, this 8ms has been subtracted from the time read from the timer so that the same result can be expected from both.

The results are presented in graphical form in Figure 24 , with the regression line and equation. From this it can be seen that the results in most cases show exact agreement and very little variation exists in the others.

The standard error of the estimate was calculated:

$s_e = 0.006$

which for a mean value of the time read from the timer ($\overline{T1} = 0.24s$) gives a percentage error of 2.5%.

Considering the possible 1% error in the displacement data this result is considered to be excellent and well within the limits of acceptable error.

Cubic spline

The duration of pre-flight was calculated from the equation

$v = u + at$

where v = vertical velocity at contact

u = vertical velocity at take-off.

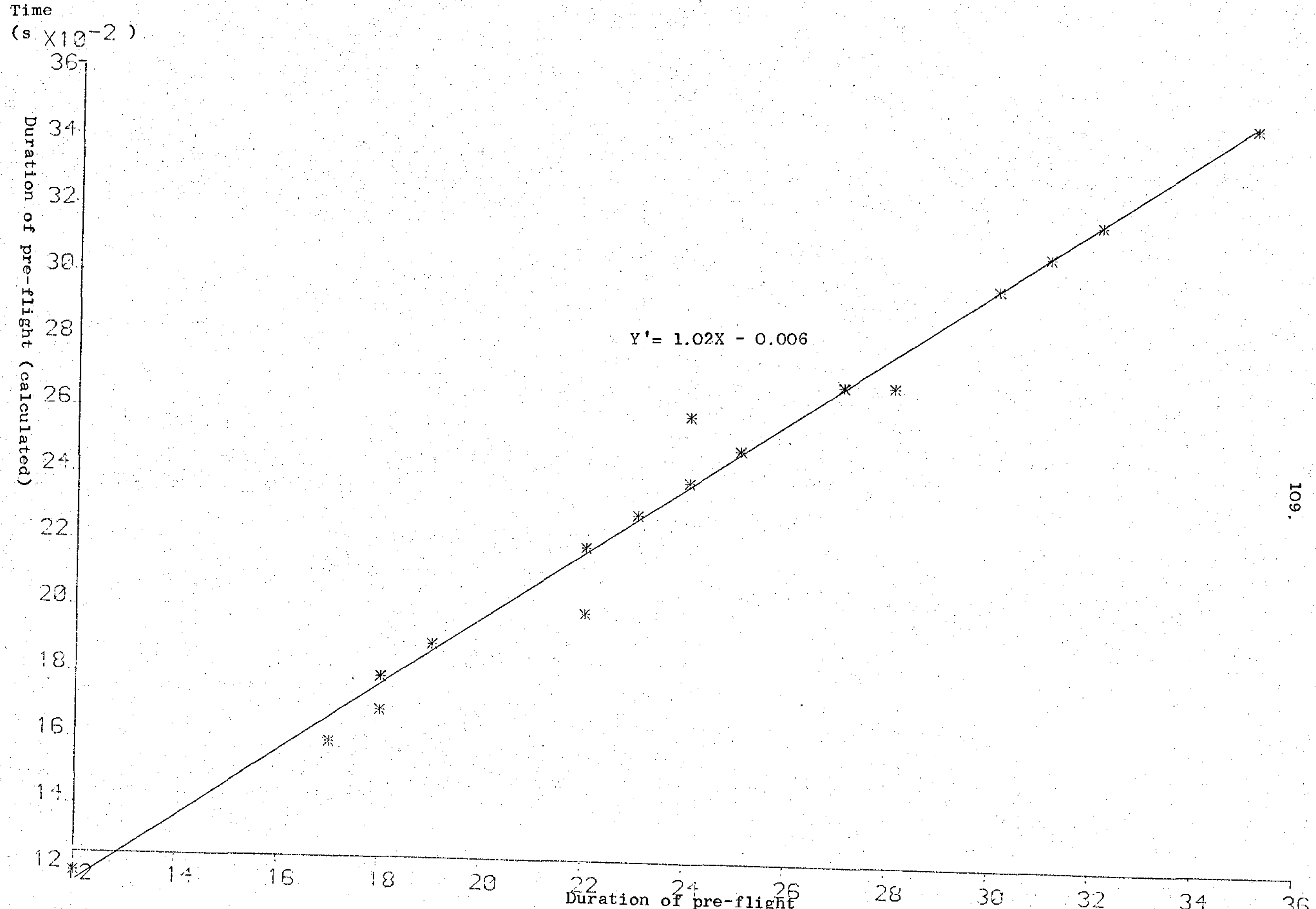


Figure 24. Regression line for the two methods of calculating duration of pre-flight (horizontal)

Degree 1

The duration of pre-flight (T1) as presented in the results (Appendix D) corresponds exactly to the duration over which these velocities were calculated.

The results, regression line and equation are presented in Figure 25. The standard error of the estimate was also calculated

$$s_e = 0.014\,s.$$

which for the mean value of T1 (0.25) gives an error of 5.6%.

This at first sight appears to be unacceptable, however it should be realized that this error represents the difference between the two velocity calculations, therefore each will have an error of 2.8%.

This result is considered to be very good and entirely acceptable within the limits of experimental error.

The two smoothing techniques have been shown to produce valid and accurate results for the velocity calculations of pre-flight, the cubic spline having the advantage over the polynomial in that it allows observations of velocity to be made during contact.

Prediction of post-flight displacement from the pre-flight and contact phases.

The results for the six subjects, from Experiment 1, on three vaults: the layout squat, handspring and Yamashita vaults, are summarised and presented in the following Tables: 8,9 and 10. The full details for each subject, from which these tables were calculated, may be found in Appendix D. A performance criterion score was calculated for each vault for each subject, as described in the previous chapter, based upon the flight path in the last critical phase of the vault. The mean value of this score and its standard

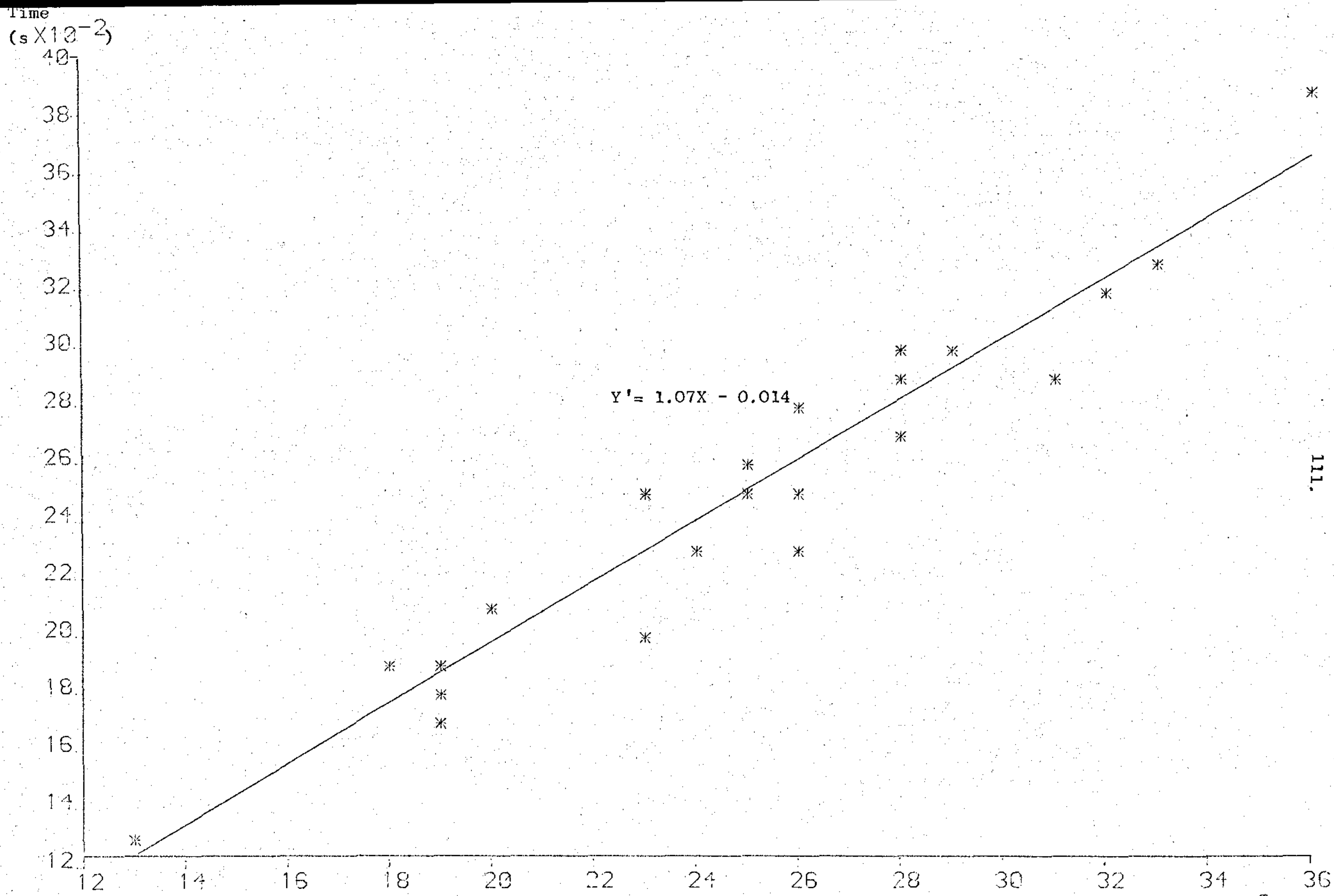


Figure 25. Regression line for the two methods of calculating pre-flight duration (vertical)

Degree I

deviation and range are also presented.

One performance (DMY) has been omitted from this analysis due to poor performance, where the vault on a national scale would have rated lower than 7.2 points.

Finally, a correlation coefficient was calculated between each measured biomechanical variable and overall post-flight performance as measured by the criterion score. These coefficients are also presented in the tables.

The tables are arranged so that all data from the two initial phases of the vaults are grouped for each variable. From these tables it can be seen that several variables correlate well (i.e. $r \geqslant 0.74$) with the post-flight performance score.

<u>The layout squat vault</u>

When results for the layout squat vault are considered it can be seen that this vault has been performed with a short duration of pre-flight, a high horizontal take-off velocity and therefore a short horizontal displacement.

Duration of pre-flight correlates negatively with the score ($r = -0.796$) as does horizontal displacement (-0.867) and this indicates that within the range of horizontal velocities shown by the subjects (3.54 - 4.07$m.s^{-1}$) those who had a short pre-flight were generally able to obtain a good result in post-flight.

Take-off vertical velocity is less in this vault than the other two vaults, however with the short duration of pre-flight vertical velocity at horse contact is maintained and is positively correlated with score. Indicating that the staircase effect between pre-flight and contact is important in obtaining a good post-flight.

Table 8.

Pre-flight phase results

		VAULTS Layout Squat n = 6 Mean (S.D.)	Layout Squat r^x	Handspring n = 6 Mean (S.D.)	Handspring r^x	Yamashita n = 5 Mean (S.D.)	Yamashita r^x
PRE-FLIGHT VARIABLES	T1 Duration (s)	0.24 (0.03)	-0.790*	0.30 (0.05)	-0.672	0.27 (0.05)	0.322
	VX1 Horizontal Velocity ($m.s^{-1}$)	3.82 (0.20)	0.347	3.64 (0.15)	0.690	3.59 (0.33)	0.680
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.24 (0.20)	-0.342	3.85 (0.15)	-0.065	3.84 (0.16)	0.371
	TH1 Take-off Angle (degrees)	79.4 (5.0)	0.237	83.1 (4.1)	-0.810*	82.3 (5.5)	-0.686
	X1 Horizontal Displacement (m)	0.94 (0.08)	0.867*	1.10 (0.17)	-0.655	1.00 (0.16)	0.790*
	Z1 Vertical Displacement (m)	0.52 (0.07)	-0.433	0.71 (0.07)	-0.487	0.67 (0.09)	0.398
	THDOT Angular Velocity ($deg.s^{-1}$)	243 (39)	-0.107	317 (30)	0.793*	316 (20)	0.1431
	TH2 Contact Angle (degrees)	183.6 (16.6)	0.412	156.8 (11.7)	0.194	154.9 (23.8)	-0.636
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	0.87 (0.30)	0.740*	0.88 (0.44)	0.774*	1.16 (0.42)	-0.430

x The correlation with the criterion performance score.

* Significant at $\alpha = 0.05$, one tail.

Table 9.

Contact phase results

CONTACT VARIABLES	Layout Squat n = 6 Mean (S.D.)	r^x	Handspring n = 6 Mean (S.D.)	r^x	Yamashita n = 5 Mean (S.D.)	r^x
T2 Duration (s)	0.22 (0.04)	-0.997*	0.33 (0.08)	-0.867*	0.25 (0.04)	-0.223
X2 Horizontal Displacement (m)	0.65 (0.08)	-0.797*	0.83 (0.18)	-0.729*	0.70 (0.16)	-0.128
Z2 Vertical Displacement (m)	0.24 (0.04)	0.399	0.30 (0.07)	0.653	0.34 (0.06)	0.121
FX1 Average Horizontal Compressive Force (N/body weight)	-1.17 (0.25)	0.193	-0.95 (0.27)	-0.099	-0.63 (0.77)	-0.048
FZ1 Average Vertical Compressive Force (N/body weight)	2.13 (0.46)	0.624	1.40 (0.28)	0.397	1.37 (0.42)	0.329
FX2 Average Horizontal Repulsive Force (N/body weight)	-0.14 (0.11)	-0.358	-0.29 (0.09)	-0.356	-0.13 (0.19)	-0.122
FZ2 Average Vertical Repulsive Force (N/body weight)	0.78 (0.08)	0.383	0.84 (0.11)	0.403	1.03 (0.01)	0.255
IX Horizontal Impulse (N.s/body mass)	-0.91 (0.31)	0.206	-1.38 (0.37)	0.327	-0.97 (0.27)	-0.821*
IZ Vertical Impulse (N.s/body mass)	2.18 (0.29)	-0.430	2.97 (1.28)	-0.801*	2.53 (0.36)	0.792*

x The correlation with the criterion performance score.

* Significant at $\alpha = 0.05$, one tail.

Table 10.

Performance criterion score

Vault	Mean	S.D.	Range
Layout squat	0	1.89	(-2.45) - (+2.03)
Handspring	0.01	1.91	(-2.74) - (+3.07)
Yamashita	0.01	1.81	(-2.01) - (+1.97)

Figure 26 presents the paths of the centres of gravity of the gymnasts, with the performance criterion score awarded to each vault. These displacements are measured with a reference zero at the centre of the top of the horse. The variations in the heights of the centres of gravity at take-off are, of course, mainly due to the height of the subject, but upon landing the body configuration and angle also influence these results.

The importance of horizontal displacement in pre-flight can be observed from this graph, where the better vaulters (JB, JT) have started closer to the horse, the path is still moving upward before contact, reflecting the vertical velocity at contact, and continues with a marked upward displacement during contact. Vaulters HP and TS on the other hand commence further away from the horse than any of the other vaulters, and they are approaching the peak height of their first flight prior to horse contact. These two gymnasts also fail to gain height during contact and have a meagre post-flight.

Mean take-off angle is 79.4° and angular velocity is low, being 243 $deg.s^{-1}$, contact angle is also low, being just below the

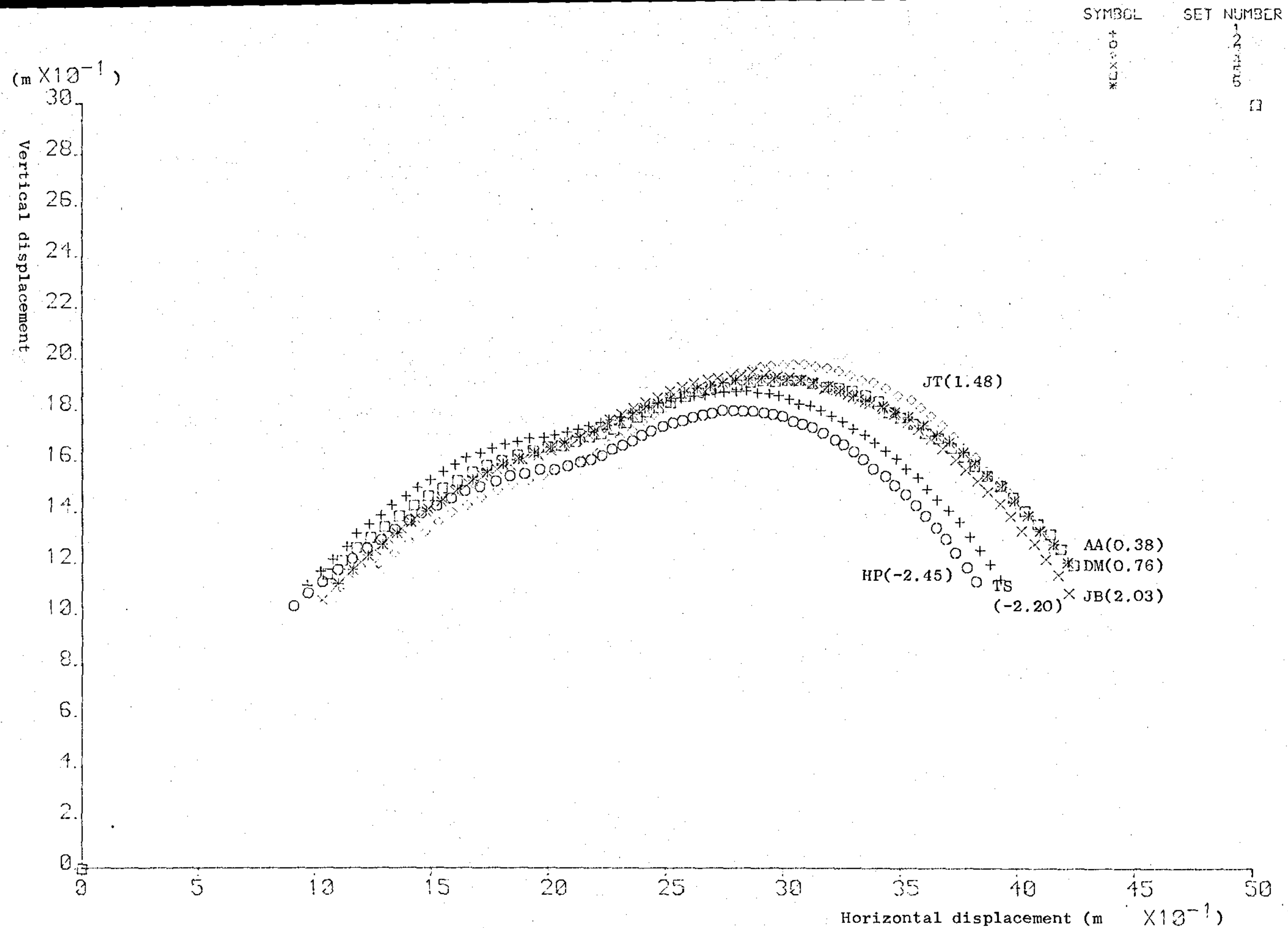


Figure 26 Layout squat vault: centre of gravity displacement

horizontal.

When the results from the contact phase are analysed, duration can be seen to be extremely well correlated with the score ($r = -0.997$) indicating that a short period of contact provides the best post-flight results. Average vertical compressive force is also moderately well correlated with the score ($r = 0.624$), indicating that those who spent less time in contact with the horse exerted a greater force in order to reverse the angular momentum of the body and gain lift from the horse. The turning effect of this reaction vector is shown in Figure 27.

For the layout squat vault, observations of the results and correlation coefficients indicate that this vault should be performed with a short pre-flight and duration of contact. The interaction of the variables of pre-flight and contact will be evaluated and used to produce predictive equations later in this chapter.

The handspring vault

For the handspring vault the rotation initiated at take-off continues in the same direction throughout the vault. This requires that the contact angle be higher than for the layout squat vault, the mean value being 156.8° or 23° above the horizontal. In order to achieve this contact angle, the angular velocity is also high $317\ deg.s^{-1}$. and this is well correlated with score ($r = 0.793$). To obtain this high angular velocity the better gymnasts were leaning forward at take-off, since angle of take-off is negatively correlated with score ($r = -0.810$). The best vaulter JB had a

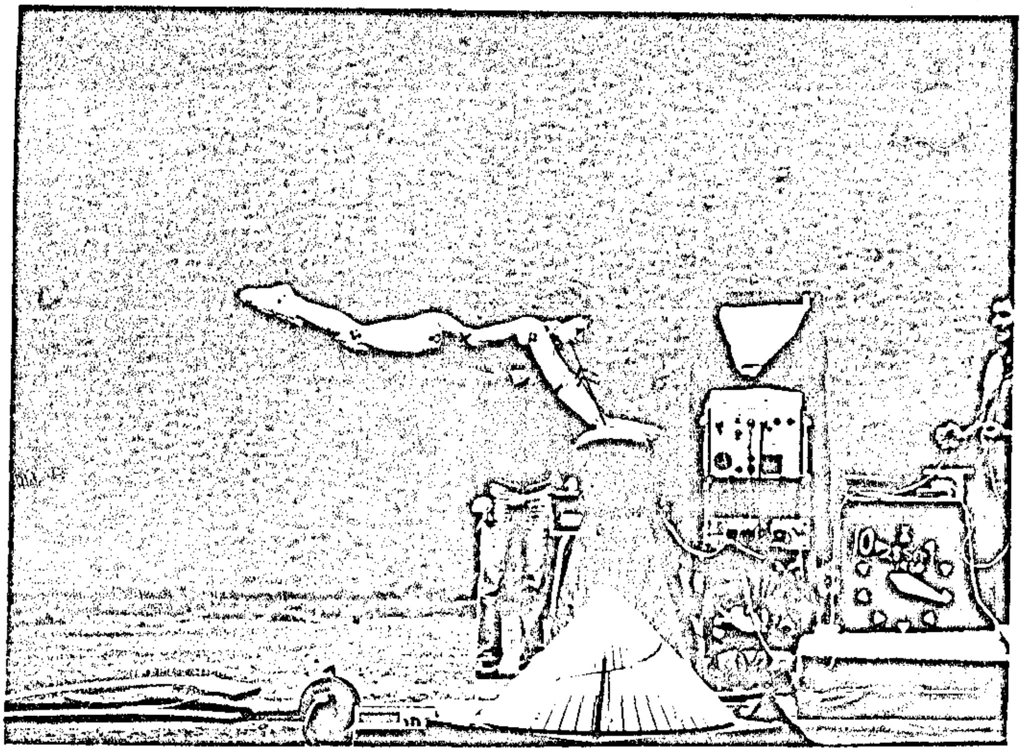


Figure 27. Turning effect of the compressive force reaction vector.

take-off angle of 75.5^{o} and an angular velocity of 357 $deg.s^{-1}$. On the other hand HP who achieved the lowest performance criterion score for this vault was much nearer the vertical at take-off, 84.9^{o}, and had a lower angular velocity, 283 $deg.s^{-1}$.

From Figure28, the graph showing the paths of the centres of gravity of the gymnasts, one can observe that JB who takes-off nearer the horse has the best result and HP whose take-off is further away has the worst. HP has also lost most of her vertical velocity by the time she reaches the horse, whereas the other vaulters, especially JB, show that the centre of gravity is still moving upwards. Vertical velocity at horse contact was well correlated with score ($r = 0.774$) and duration of pre-flight was moderately correlated with score ($r = -0.672$).

These results indicate that the use of the staircase effect between pre-flight and contact is also important in this vault.

Observation of the contact phase variables reveals that duration of contact is long (0.33s). This is largely due to the two poorer performers HP and TS who both stayed in contact with the horse for a long time, 0.43s and 0.42s respectively. The reasons for this long duration becomes apparent when one examines the preceding phase. As previously mentioned HP had a low angular velocity (283 $deg.s^{-1}$) and a low vertical velocity at contact ($0.20m.s^{-1}$). She did not have a high contact angle to compensate for the low angular velocity therefore was required to stay in contact with the horse for a long time in order to rotate the feet over the body and complete the vault. TS had a higher angular velocity 303 $deg.s^{-1}$, which is

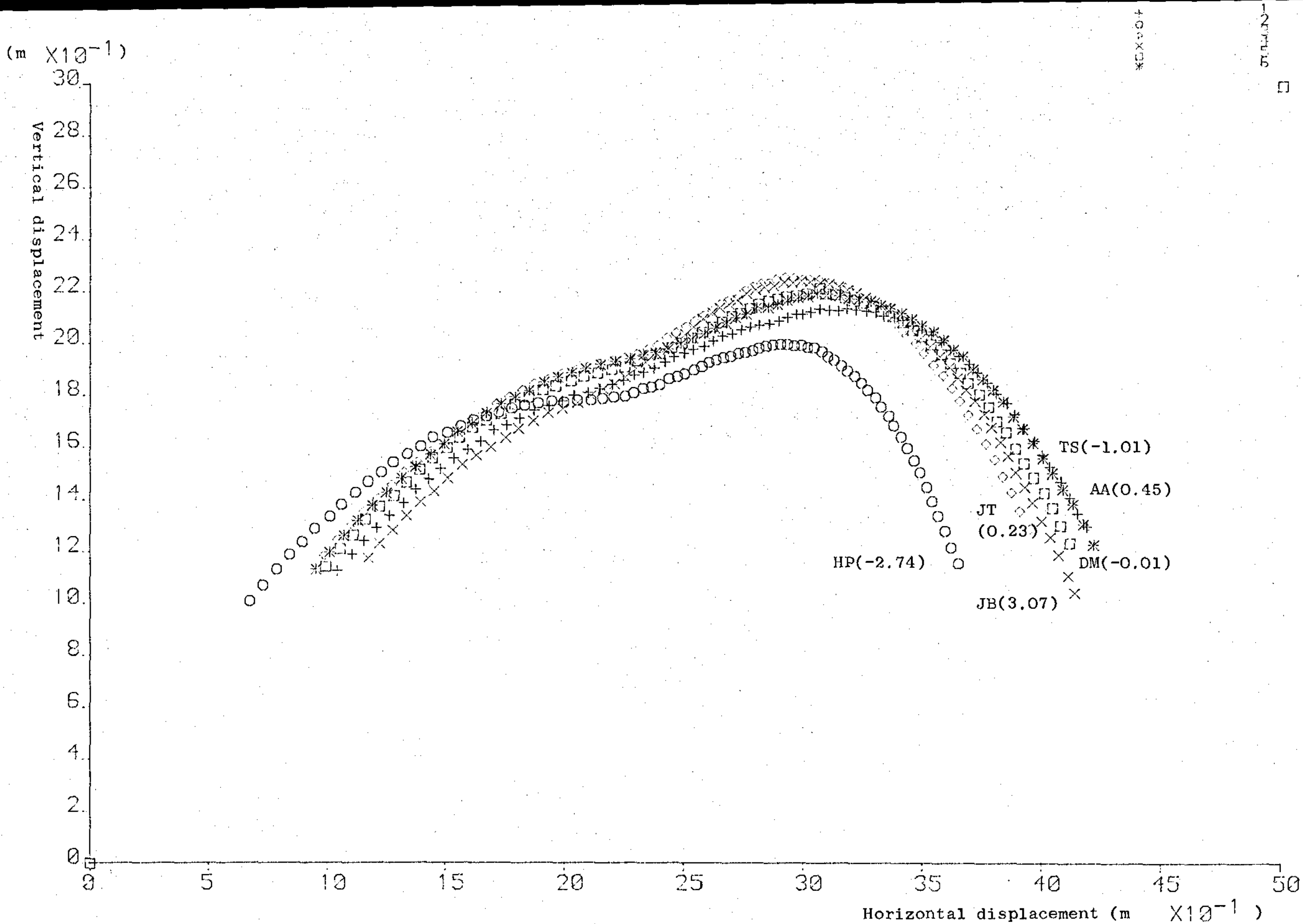


Figure 28. Handspring vault: centre of gravity displacement data.

lower than the mean values, she also had a low contact angle (169.7^{o}). In order to compensate TS flexes her elbows to increase her angular velocity, thus requiring a long duration of contact in an effort to extend them and gain lift from the horse.

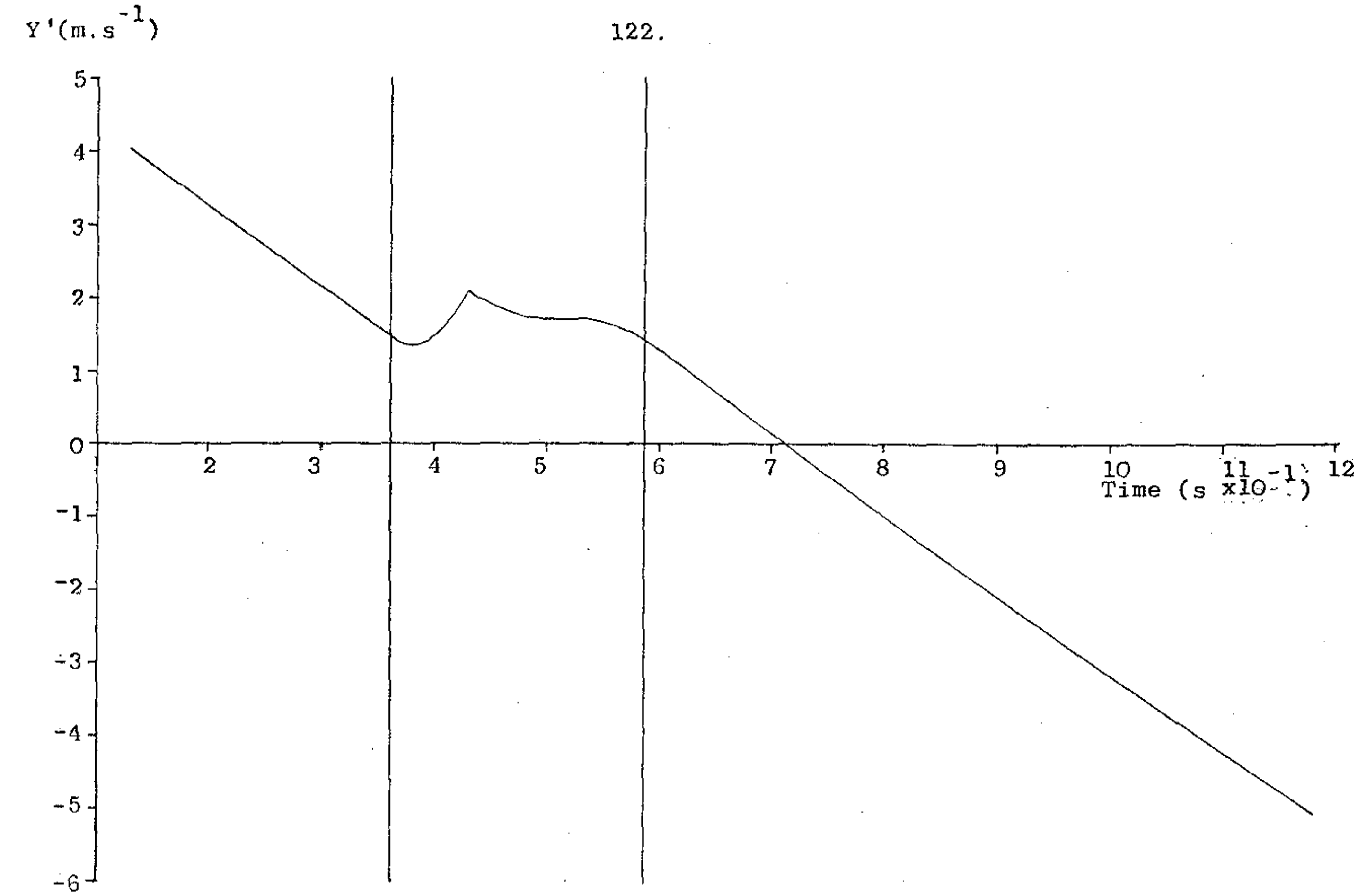
The extremely high correlation between duration of horse contact and post-flight performance is due to the inability of all gymnasts to exert an average repulsive force greater than body weight. Those who stay in contact with the horse for a long period therefore lose more vertical velocity in this phase than those who contact and leave quickly. This is reflected in the negative correlation between vertical impulse and the score ($r = -0.801$).

The best handspring vault performed by JB had the shortest contact time (0.24s). This was due to the high angular velocity which tended to lift the body from the horse, the high vertical velocity at contact and the use of the staircase effect.

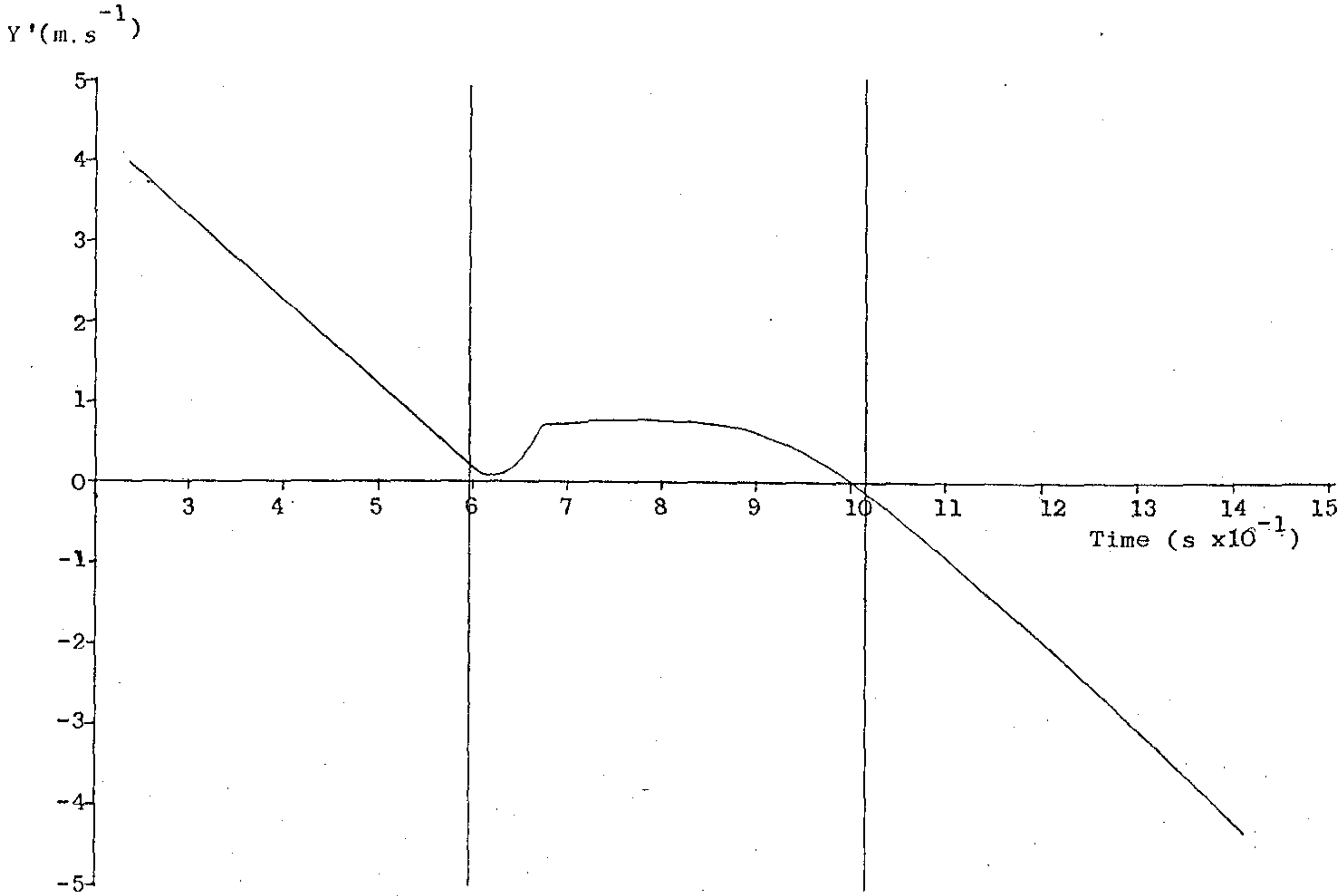
The difference in performance between JB and HP can be seen from their vertical velocity graphs (Figure 29). JB not only has a high contact velocity but also shows a marked rise in vertical velocity during the compressive phase. This is due to having very little compression and allowing the stretched body to pivot quickly around the wrists. HP shows no such peak and her velocity drops markedly toward the end of the long repulsive phase therefore leading to a poor result.

The Yamashita

The paths of the centres of gravity, given in Figure 30, clearly show that the best two vaults, performed by JB and JT, have the



JBH



HPH

Figure 29. Vertical velocity graphs: JB and HP.

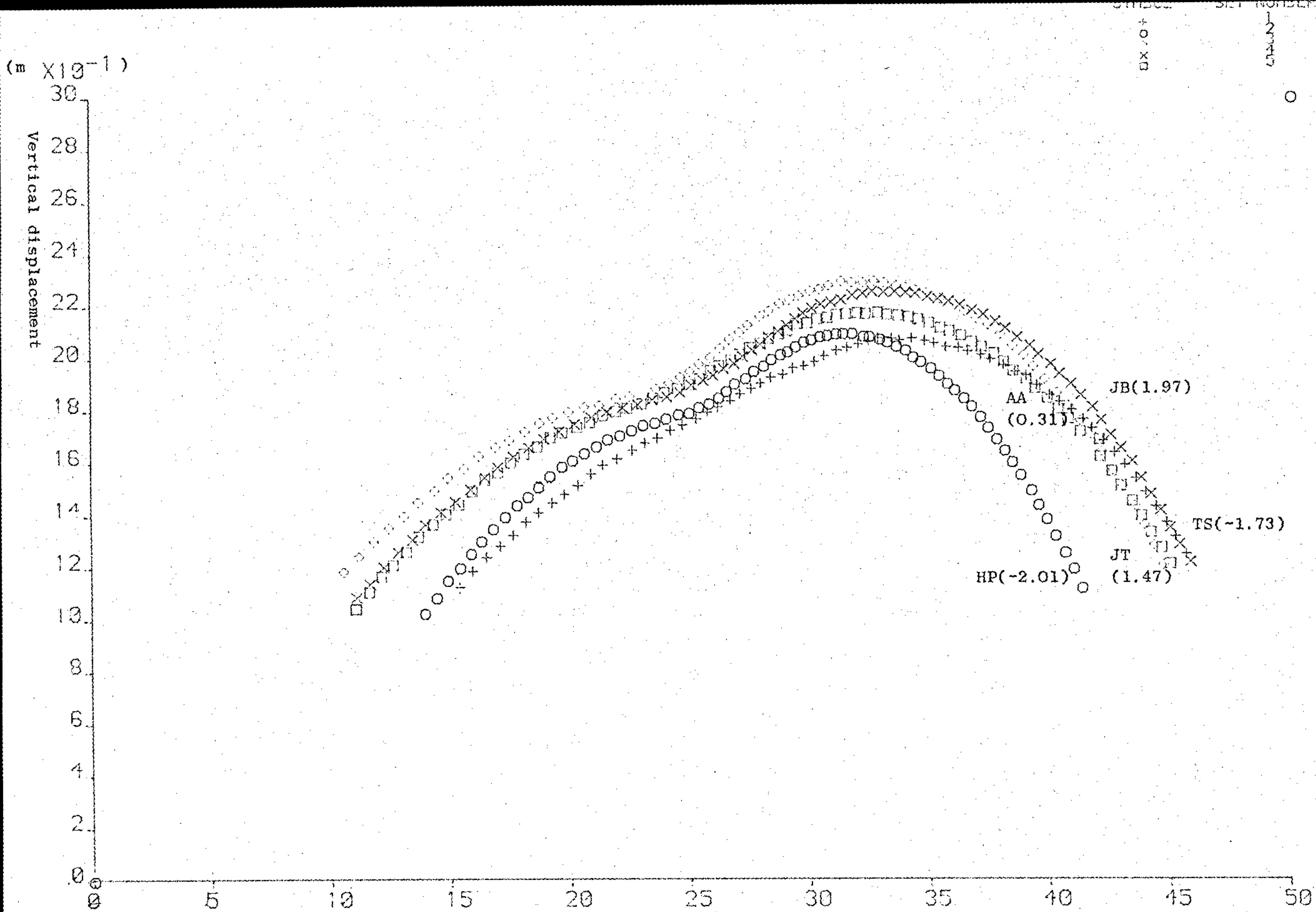


Figure 30. Yamashita vault: centre of gravity displacements.

greatest horizontal displacement in pre-flight (1.09m and 1.14m respectively). This would appear to be in direct contrast with the observations relating to the layout squat and handspring vaults. However it should be noted that the range in horizontal displacement was from 0.72m (TS the poorest performer) to 1.14m (JT), for the handspring it was from 0.87m (JB the best) to 1.32m (HP the poorest performer). The mean results for the best three vaults having values of 1.09m and 1.07m for the Yamashita and handspring respectively. Indicating that in the Yamashita the poorer performers started too close to the horse, while in the handspring they started too far away. This explains the reason why, for this vault, horizontal displacement is well correlated with the criterion performance score, positively, where $r = 0.790$. Horizontal displacement is the only pre-flight variable to be well correlated with score.

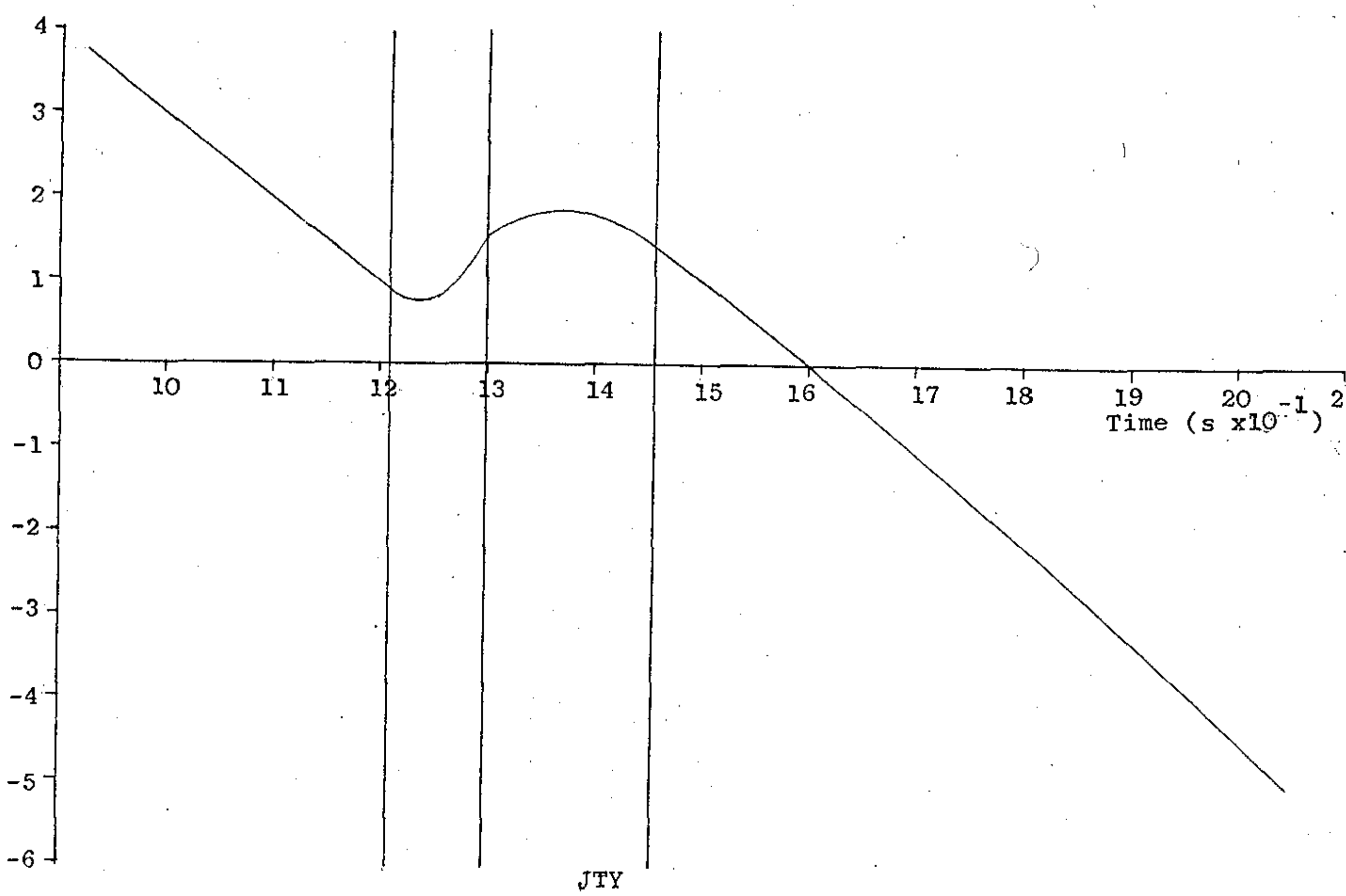
The weak, but negative, correlation between vertical velocity and contact and the score is due solely to the performance of TS who has a very high contact velocity, due to the extremely short pre-flight. However she hits the horse with a low contact angle (194.1^{o}) and thus must stay in contact with the horse for a long time where she loses most of her vertical velocity and hence has a poor post-flight.

Duration of horse contact is less in this vault than for the handspring. TS showing the longest duration ($T2 = 0.30$s) and the poorest performance. However no general pattern emerges with regard to this variable for the Yamashita.

Vertical impulse is well correlated, positively, with the post-flight result ($r = 0.792$), this may be due to none of the subjects showing an extremely long duration of contact and the range being quite small (T2: 0.20 - 0.30s).

Horizontal impulse is also well correlated with score, but negatively ($r = -0.821$). This implies that the better gymnasts have a greater horizontal impulse than the poorest gymnasts, but the value is less than for the handspring vault (Yamashita: IX = 0.97, handspring: IX = 1.38). This result could in part be due to the greater pre-flight horizontal velocity shown by the better subjects (JB: VX1 = 3.59m.s^{-1}, JT: VX1 = 3.91m.s^{-1}), which has enabled greater lift to be obtained from the horse, as shown by the gain in height during post-flight (JB: ZFL = 0.12, JT: ZFL = 0.13). It appears from the vertical reaction forces that these two gymnasts have gained the lift using different techniques. JB is using a rebound technique since her average vertical compressive force is large (FZ1 = 1.82N/body weight), while JT shows the largest average repulsive force of any subject in this experiment (FZ2 = 1.22N/body weight) and is using a technique which requires more of a pushing action on the part of the gymnasts. The force traces for this gymnast (Appendix C) clearly show the differences in these two techniques as do the vertical velocity graphs (Figure 31). Where the velocity of JB reaches a peak, due to the large compressive force, drops and fails to regain the peak value shown, whereas JT continues with an increasing vertical velocity after the end of the compressive phase.

The turning effect of these reaction vectors of compression and repulsion appears to be small, especially in the repulsive phase, as shown in Figures 32 and 33.



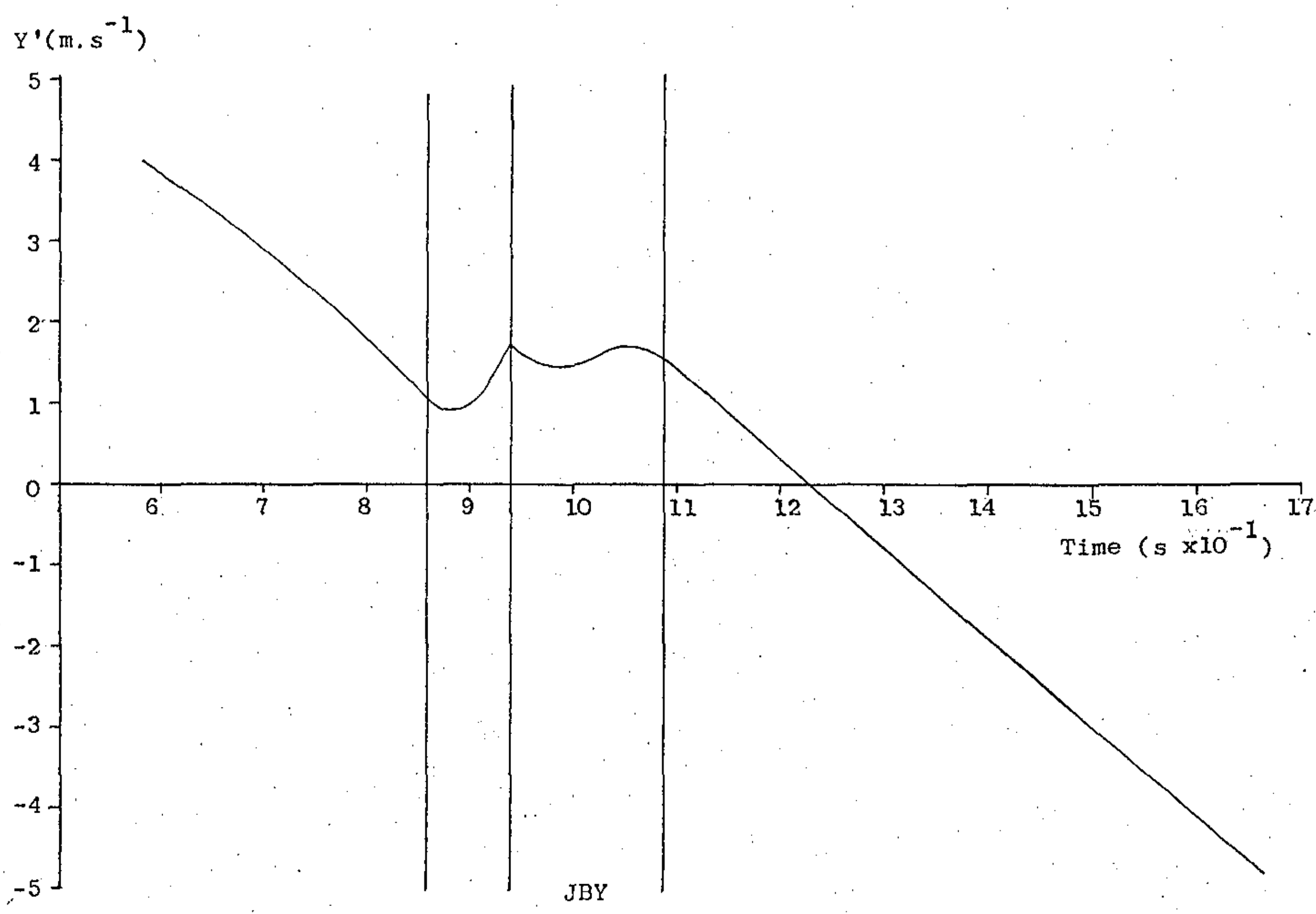


Figure 31. Vertical velocity graphs: JT and JB.

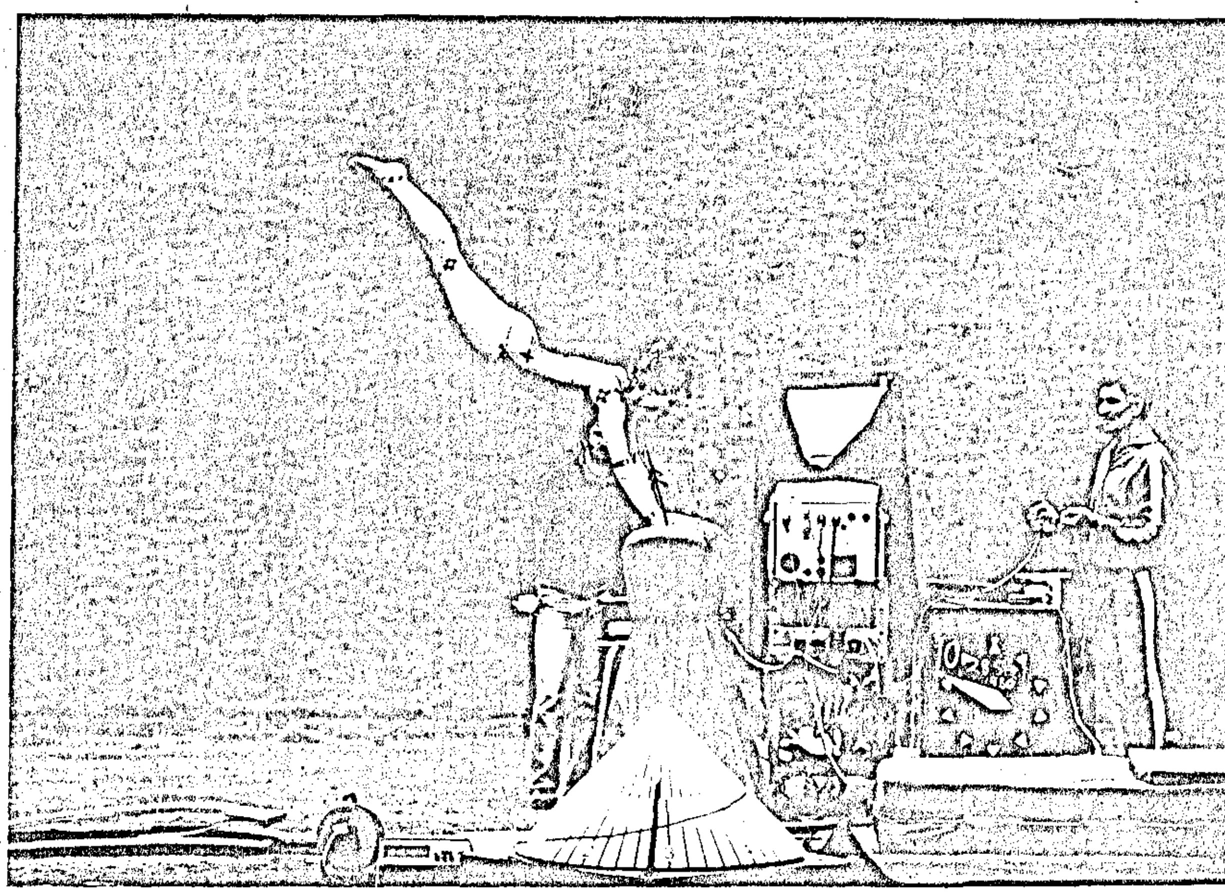


Figure 32. The turning effect of the compressive force reaction vector.

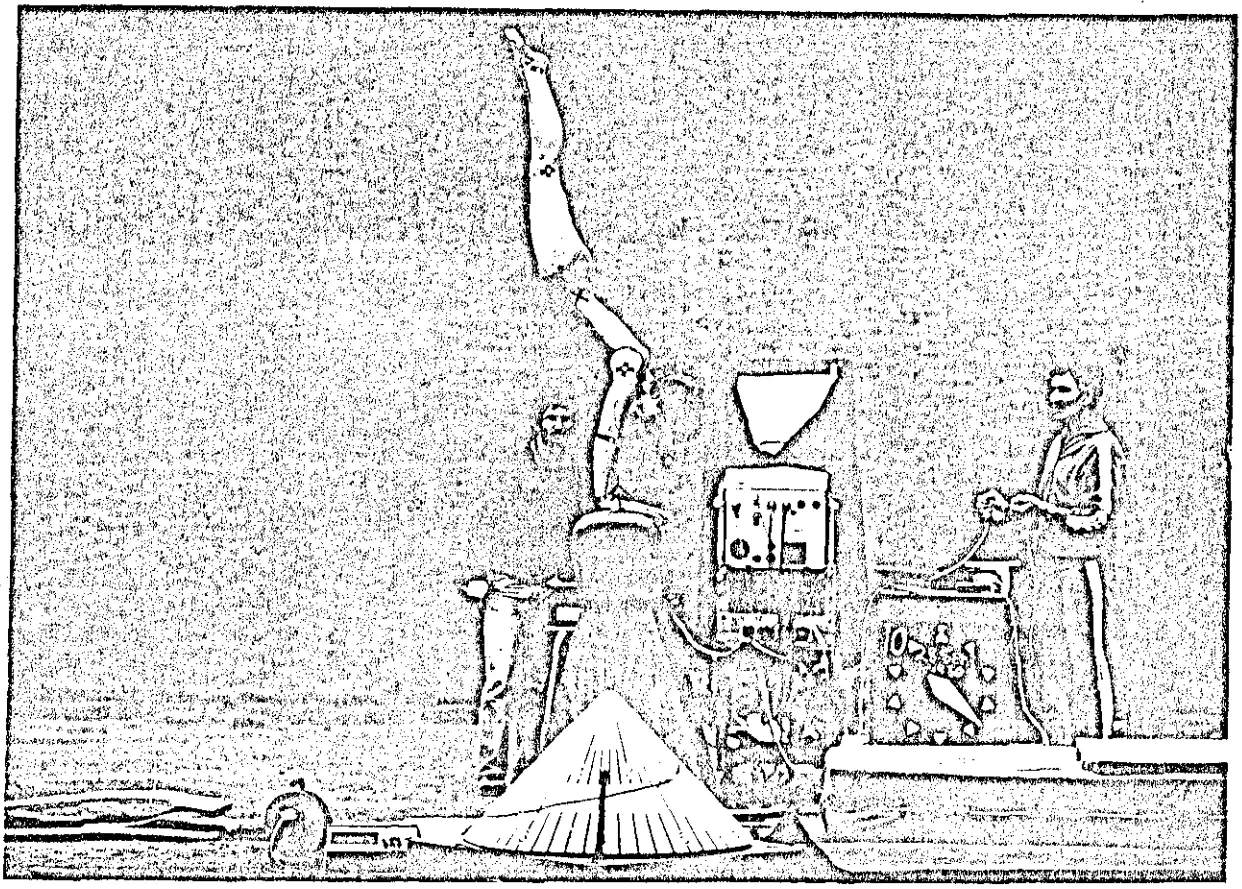


Figure 33. The turning effect of the repulsive force reaction vector.

Predictive equations

Multiple regression equations were used to determine whether the outcome of a vault could be predicted from either or both the pre-flight and contact phases. The group was initially thought to be fairly homogeneous. However in practice performances, though of a good standard, ranged widely, as previously discussed. The patterns of performance that have become apparent from the observations were subjected to a regression analysis to determine the extent to which these interact to determine post-flight.

The layout squat vault

Prediction of post-flight from the pre-flight phase

Initially post-flight was predicted from three pre-flight variables and a regression equation calculated, viz:

$$Z = 53.74 - 18.04X1 - 0.12TH2 - 64.35T1$$

where X1 = horizontal displacement

TH2 = contact angle

T1 = duration

This prediction accounted for 99.8% of the variance of Z which is significant at $\alpha = 0.001$.

The equation indicates that a short pre-flight with a high contact angle will produce the best results. It should be noted that other variables, which were well correlated with the score did not appear in the equation, due to their correlation with the variables that did appear.

Vertical velocity at horse contact was not only well correlated with the post-flight performance criterion ($r = 0.740$), but also correlated moderately with duration of pre-flight ($r = -0.679$). Similarly vertical displacement during pre-flight correlates well with duration of pre-flight ($r = 0.850$) and horizontal displacement ($r = 0.722$).

These variables are all related by the Newtonian laws of parabolic motion, despite this they do not correlate perfectly because of the range in take-off velocity. However they can be seen to interact significantly to produce a short pre-flight, which with the use of the staircase effect between pre-flight and contact produces the best post-flight results.

The appearance of a high contact angle playing an important role in producing a good result should be interpreted within the results shown by these performers. The highest contact angle was 169.9^{o}, which is only 10^{o} above the horizontal and a long way below the former 45^{o} requirements shown in the 1970 I.G.F. Code of Points.

The regression equation, in conjunction with the correlation of other variables obeying the laws of parabolic motion indicate that a low, short, but constantly rising pre-flight will produce the best results in post-flight. Therefore, for the layout squat vault the subsidiary hypothesis can be accepted where:

H2: The outcome of a vault is a function of pre-flight.

<u>Prediction of post-flight from the contact phase</u>

Measures of performance during contact were also used to predict the outcome of the vault. The values for these measures for each subject are presented in Appendix D and summarised in Table 8.

Of these duration of contact (T2) accounted for 99.4% of the variance in the criterion variable, post-flight performance, which was significant at $\alpha = 0.001$. Including as a second variable the next 'best' variable available, understandably adds little to the predictive power of the equation, the maximum variance rising by only 0.2% to 99.6%. Consequently it is clear that there was no advantage in adding further terms to the regression equation, so a predictive equation based only on one variable was selected, viz:

$$Z = 10.36 - 47.02T2$$

where T2 = duration of contact.

Considering the foregoing one might at first be tempted to conclude in favour of the originally postulated hypothesis (H3) that the outcome of a vault is a function of the interactions between the vaulter and the horse during contact. However as T2 can, in turn, be predicted almost wholly (99.8%) from pre-flight variables, viz:

$$T2 = -9.09 + 3.13X1 + 2.48TH2 + 1.58T1$$

where X1 = horizontal displacement

TH2 = contact angle

T1 = duration of pre-flight

then clearly such a conclusion should not be drawn, but the alternative that pre-flight can predict post-flight be accepted instead.

The handspring vault

Prediction of post-flight from the pre-flight phase

The regression equation for predicting height and distance in post-flight from pre-flight is as follows:

$$Z = 19.88 - 0.26TH1 + 2.16VZ2$$

where TH1 = take-off angle

VZ2 = vertical velocity at contact

This equation accounts for 73.0% of the variance of Z (significant at $\alpha = 0.1$).

Angular velocity, although well correlated with the performance criterion score ($r \approx 0.793$), does not appear in this equation since it is correlated with take-off angle ($r = -0.540$) and vertical velocity at contact ($r = 0.600$).

In light of the above equation and its predictive efficiency suggestions may be made about pre-flight behaviour of the gymnast in the handspring vault. She should be leaning well forward at take-off, have a high angular velocity in flight and a high vertical velocity at contact.

Within the limits of take-off velocity, height (Z1), distance (X1) and duration of pre-flight (T1), are also significant and highly correlated with vertical velocity at horse contact (VZ2), ($r_{Z1.VZ2} = -0.829$, $r_{X1.VZ2} = -0.950$, $r_{T1.VZ2} = -0.975$). Had the take-off velocity been identical for all subjects these correlations should have been perfect, according to the equations of parabolic motion:

$$v = u + at$$

and $$s = ut + \tfrac{1}{2}at^2$$

However the mean (S.D.) of horizontal velocity was 3.65 (± 0.29) $m.s^{-1}$. These results indicate that within the range of take-off velocity shown by these subjects velocity at horse contact will be greater for a short pre-flight. This in combination with a high contact angle and angular velocity in flight, will produce the best post-flight results.

Prediction of post-flight from the contact phase

When contact variables were analysed it was again found that duration was the most important, again negatively correlated with the performance criterion score ($r = -0.867$, significant at $\alpha = 0.025$). Vertical impulse was also well, and negatively, correlated with performance ($r = -0.801$, significant at $\alpha = 0.025$). This is contrary at least to the casual expectation that a large contact impulse would lead to a high subsequent flight. As discussed previously this is due to the long period of contact shown by two subjects HP and TS. Vertical impulse is well correlated with duration of contact ($r = 0.825$), this is to be expected where there is a large range in the duration of contact. Vertical impulse is not included in the predictive equation:

$$Z = -1.74 - 15.20T2 + 15.03Z2 + 1.52FZ1$$

where T2 = duration

Z2 = vertical displacement

FZ1 = average vertical compressive force

which accounts for 99% of the variance of Z and is significant at $\alpha = 0.05$.

This equation indicates that a short duration, a large vertical displacement and a high vertical compressive force during contact will produce the best post-flight.

However duration of contact can be predicted in turn from pre-flight variables:

$$T2 = -3.99 + 0.01TH1 + 0.01TH2 + 1.88Z1$$

where TH1 = take-off angle

TH2 = contact angle

Z1 = vertical displacement

this accounts for 93.1% of the variance of T2 and is significant at $\alpha = 0.05$.

Vertical displacement during contact is extremely well correlated with duration of pre-flight ($r = -0.974$) and vertical velocity at contact ($r = 0.929$). The above results indicate that the post-flight and contact phases are dependent upon pre-flight performance. Therefore the subsidiary hypothesis H2 may be accepted where:

H2: The outcome of a vault is a function of pre-flight.

The Yamashita

Prediction of post-flight from the pre-flight phase

The predictive equation for post-flight displacement from the pre-flight variables is:

$$Z = -13.88 + 17.09X1 + 4.21VZ2 - 0.1TH1$$

where X1 = horizontal displacement

VZ2 = vertical velocity on contact

TH1 = take-off angle

This accounts for 99.3% of the variance of Z and is significant at $\alpha = 0.1$. The lack of a high level of significance being obtained when such a large proportion of the variance of Z has been accounted for, is due to the small number of subjects ($n = 5$).

This equation indicates that the gymnast should be leaning well forward at contact, have a long horizontal displacement and a great velocity at horse contact in order to achieve a good post-flight, however these results may only be applicable within the range of performance shown by the gymnasts studied.

The subsidiary hypothesis can however be accepted for these performers where:

H2: The outcome of a vault is a function of pre-flight.

But this needs to be further tested before any generalizations can be made to the wider range of performances.

Prediction of post-flight from the contact phase

When post-flight is predicted from contact performance the predictive equation is:

$$Z = -5.58 - 10.29IX + 6.33FX1 + 0.97FZ1$$

where IX = horizontal impulse

FX1 = average compressive force

FZ1 = average vertical compressive force

Of these variables only horizontal impulse is well correlated with score, where $r = -0.821$ ($\alpha = 0.05$). However vertical impulse is also well correlated with score ($r = 0.792$), but does not appear in the equation since it is also well correlated with horizontal impulse ($r = -0.863$). As previously discussed, the gain in vertical velocity during horse contact, may be a function of the interaction between the horizontal and vertical impulses and the high correlation between these two would tend to support this view.

Due to the small number of subjects who performed the Yamashita ($n = 5$), the equations which predict the contact variables from pre-flight tend to reflect random variations rather than patterns dictated by the mechanics of performance. It could be that the contact phase is independent of pre-flight, however pre-flight has been shown to account well for post-flight performance therefore it is likely that had more subjects been used the relationship between pre-flight and contact would also have become apparent.

The subsidiary hypothesis H3: The outcome of a vault is a function of the interaction between the vaulter and the horse during contact, is thus rejected.

Validation of predictive equations

In order to validate the predictive equations it was necessary to test them on performances conducted under different conditions.

The results from Experiment 2 were used in the validation. These vaults were all performed indoors, where a full approach run was available for the use of the gymnasts.

Three gymnasts, who were not performers in Experiment 1, produced their 'best' vaults, and another subject JT modified her pre-flight in the layout squat and handspring vaults. These seven vaults were then used to test the predictive equations.

The criterion on which to accept or reject these predictive equations was based upon a comparison of the two rankings of the vault from the two performance criterion scores.

The first performance criterion score was calculated as for the subjects in Experiment 1, using the following equations:

$$ZXFL = (XFL - \overline{XFL}) / (S.D._{(XFL)})$$

$$ZZFL = (ZFL - \overline{ZFL}) / (S.D._{(ZFL)})$$

where ZXFL = the standardised score for post-flight horizontal displacement

ZZFL = the standardised score for post-flight vertical displacement

The mean and standard deviation used in these equations were from the subjects of Experiment 1 only.

These standardised scores for post-flight horizontal and vertical displacements were then summed to produce the performance criterion score.

The second performance criterion score was calculated from the predictive equations.

Each of these two scores was then ranked with the subjects of Experiment 1. If the two rankings were within one position of each other then the equation was considered acceptable.

The layout squat vault

The mean and standard deviation for the six subjects in Experiment 1 were calculated:

$\overline{XFL} = 1.45m$ S.D. $= 0.24m$

$\overline{ZFL} = 0.05m$ S.D. $= 0.03m$

The results for BSTV (XFL = 1.71m, ZFL = 0.07m) were used to calculate the first performance criterion score:

$Z_1 = 1.75$

This is within the range shown by the subjects, and ranked in the second position.

The pre-flight multiple regression equation for predicting the second criterion score requires a short pre-flight with a high contact angle, where:

$$Z_2 = 53.74 - 18.04X1 - 0.12TH2 - 64.35T1$$

For BSTV: X1 = 1.14m

TH2 = 175.9degrees

T1 = 0.26s

therefore Z1 = -4.67

which gives a ranking of seven. The large difference indicates that the equation may not be valid for a vault performed under different conditions.

The reason for this becomes apparent when the ranges of the independent variables for the subjects in Experiment 1 are compared to the values for BSTV. Both duration of pre-flight and contact angle are within the ranges shown by the other performers, however horizontal displacement is outside the range shown: 1.14m c.f. 0.83 - 1.05m. It is because of this large horizontal displacement that a poor score has been predicted. However BSTV also showed a horizontal velocity well above the range shown by the other performers, $4.49 m.s^{-1}$ c.f. $3.54 - 4.07 m.s^{-1}$. The range shown by the six performers is quite small and appears to be a limiting factor in the application of the equation to other performances.

These results indicate that horizontal displacement may be less important in the wider realm than duration of pre-flight, since horizontally,

$$s = vt$$

and if horizontal velocity is large, the duration of pre-flight will still be short, even though the displacement is increased.

The principles previously discussed with regard to the staircase effect and its importance in producing a good post-flight for the layout squat vault are still valid, but the equation cannot be used successfully outside the range of horizontal velocity shown by the six subjects.

Of the two layout squat vaults performed by JT, one has a horizontal velocity value within this range (JTTVL: $VX1=3.97 m.s^{-1}$), the other is just outside (JTTVH: $VX1=4.19 m.s^{-1}$).

These two vaults were included in the analysis to verify further the effect of pre-flight on post-flight. Not only must the criterion on ranking be met, but these two vaults must be ranked in the correct order relative to each other, if the equations are to be validated within the limits of horizontal velocity.

The vault with the high pre-flight (JTTVH) showed post-flight displacements of 1.58m horizontally and 0.16m vertically.

Therefore $Z_{1H} = 4.21$

For JTTVL, post-flight horizontal and vertical displacements are 1.59 and 0.14m respectively,

therefore $Z_{1L} = 3.58$.

These results give both vaults a ranking of one and indicate that the vault with the high pre-flight was the better of the two.

For the predictive equation:

$$Z_2 = 53.74 - 18.04X1 - 0.12TH2 - 64.35T1.$$

JTTVH and JTTVL have the following values for the independent variables:

JTTVH	JTTVL
X1 = 0.74m	X1 = 0.54m
TH2 = 206.6 degrees	TH2 = 221.2 degrees
T1 = 0.17s	T1 = 0.13s

therefore $Z_{2H} = 4.65$ and $Z_{2L} = 9.09$

Rank = 1 Rank = 1

While the criterion scores calculated from the equation give the correct ranked position and excellent agreement between the two scores calculated for JTTVH, it can be seen that the order of the two vaults, relative to each other has been reversed. The predictive equation indicating that JTTVL is a better vault than JTTVH. This shows further limitations which must be placed on the application of the equation.

Vault JTTVL was performed with an extremely short duration of pre-flight, T1 = 0.13s, and horizontal displacement, X1 = 0.54m. These values lead to the prediction of a high criterion score which was not justified.

However vault JTTVH was also outside the range shown by the other performers on these two variables (T1 = 0.17s, c.f. 0.20-0.28s; X1 = 0.74m, c.f. 0.83-1.05m) but the two scores for this vault were in excellent agreement.

These results show that there is some flexibility in the equation, but not to the extent of almost halving the duration of pre-flight.

The handspring vault

The mean and standard deviation for the post-flight results of the six subjects performing the handspring vault are presented below:

$\overline{XFL} = 1.16m \qquad S.D. = 0.27m$

$\overline{ZFL} = 0.03m \qquad S.D. = 0.04m$

For SCH, XFL = 1.63m and ZFL = 0.09m

therefore $Z_1 = 2.99$

and a rank of two.

From the predictive equation

$$Z_2 = 19.88 - 0.26TH1 + 2.16VZ2$$

where for SCH: TH1 = 80.4degrees

VZ2 = $1.15m.s^{-1}$

therefore $Z_2 = 1.46$

this also gives the second position in the ranking. Horizontal velocity for SCH is only just outside the range shown by the other performers, $3.98 m.s^{-1}$, c.f. $3.45 - 3.89 m.s^{-1}$, the other pre-flight results shown by SCH are within the ranges from Experiment 1.

However the two handspring vaults performed by JT show horizontal velocity results outside $3.45 - 3.89 m.s^{-1}$ (JTHH: VX1 = 4.23, JTHL: VX1 = 4.19).

JTHH	JTHL
XFL = 1.66	XFL = 1.81
ZFL = 0.09	ZFL = 0.10
therefore $Z_{1H} = 3.35$	and $Z_{1L} = 3.91$
Rank = 1	Rank = 1

The criterion score calculated from post-flight indicates that both of these vaults are better than any performed by the six subjects and that the vault performed by JT with the low pre-flight is better than that with the high pre-flight.

For the equation:

$$Z_2 = 19.88 - 0.26 TH1 + 2.16 VZ2$$

where

JTHH	JTHL
TH1 = 76.5	TH1 = 68.3
VZ2 = 1.26	VZ2 = 1.73
therefore $Z_{2H} = 2.71$	and $Z_{2L} = 5.86$
Rank = 2	Rank = 1

The equation has been able to predict accurately to within one position the performance of both these vaults, and has ranked them correctly relative to each other. Indicating the post-flight can be predicted with some accuracy from the pre-flight performances and this indicates that the pre-flight should be short, with a low take-off angle, a high angular velocity and a constantly rising path of the centre of gravity.

The Yamashita

Upon the coach's advice no subject was asked to perform this vault with modifications in pre-flight, since it is a more difficult vault to perform and the safety of the gymnasts' may have been put at risk.

As a consequence only one vault is presented here to evaluate the predictive equation. The vault was performed by AG and has the second highest post-flight achieved by any subject in this study.

ZFL = 0.22m

XFL = 1.48m

When compared to the mean results for the other subjects' performances of the Yamashita:

$\overline{XFL} = 1.52$ S.D. = 0.18

$\overline{ZFL} = 0.09$ S.D. = 0.04

for AGY $Z_1 = 3.03$

This is ranked as the best vault.

From the predictive equation:

$$Z_2 = -13.88 + 17.09X1 + 4.21VZ2 - 0.1TH1$$

where for AGY: X1 = 0.79m

VZ2 = 1.88m.s^{-1}

TH1 = 57.5degrees

therefore $Z_2 = 1.79$

which is ranked in the second position. This gives an acceptable result for agreement between the two post-flight criterion scores.

Of interest in the performance of this vault is the technique used to gain such a high post-flight.

From the vertical velocity graph (Figure 34) it can be seen that AG contacts the horse with an extremely high vertical velocity (VZ2 = $1.88 m.s^{-1}$) and appears to be using the technique shown by JT during the contact phase, where a large force is applied during the repulsive phase. The vertical velocity upon leaving the horse is also large for AGY (VZ3 = $1.91 m.s^{-1}$), which gives a long duration of post-flight, tending to counteract the loss in horizontal velocity shown during contact (VX1 = $4.11 m.s^{-1}$, VX3 = $2.07 m.s^{-1}$).

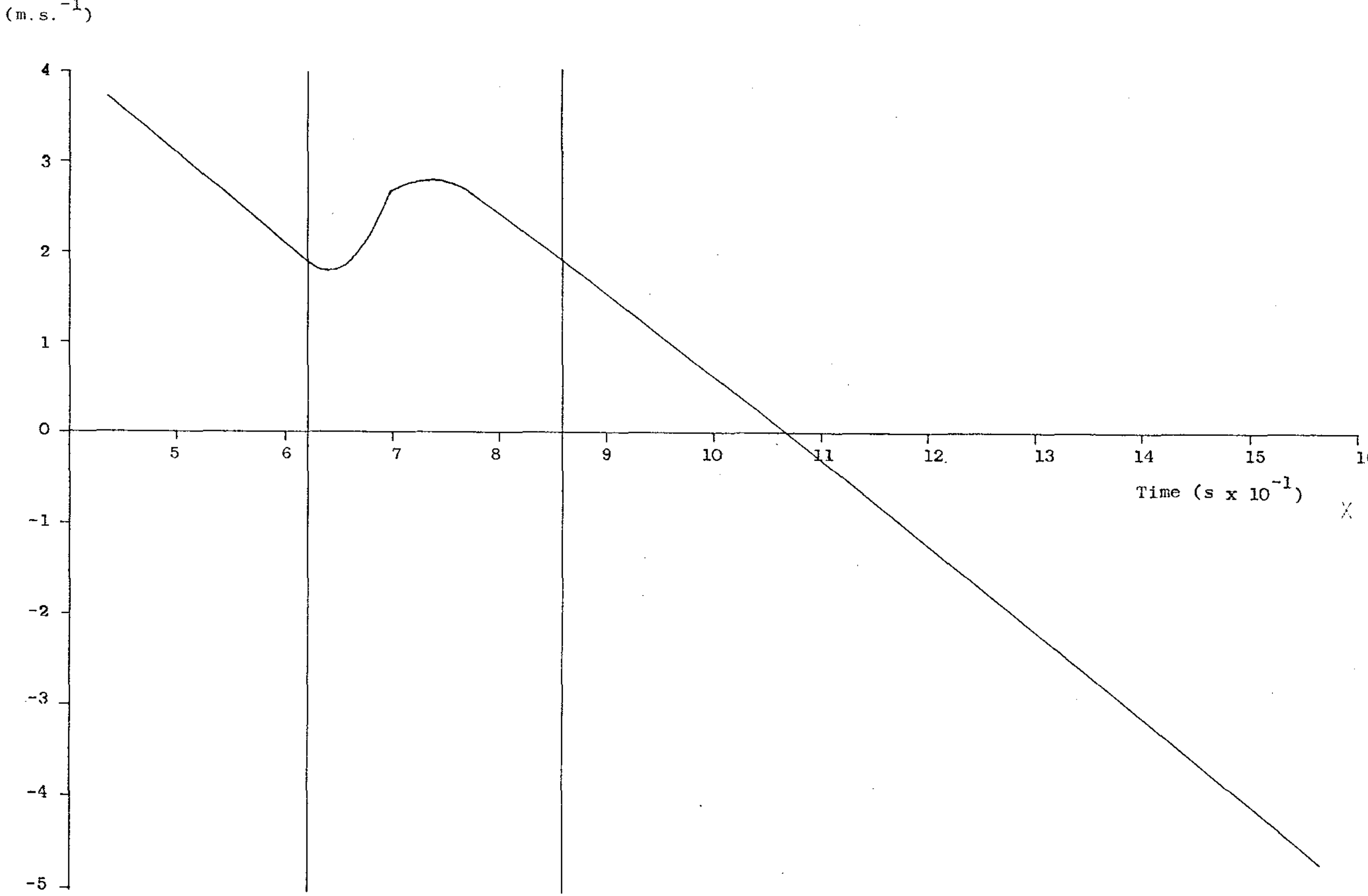


Figure 34. Vertical velocity graph:AGY.

PART 3

Determination of the differences between the four types of vaults.

The three vaults so far discussed can be classified according to post-flight complexity. This classification is based upon the angular momentum requirements of post-flight.

For the layout squat vault the post-flight angular momentum is in a negative direction, therefore this vault is determined to be the least complex. The angular momentum requirements, in a positive direction, are less for the Yamashita than the handspring, since the angular displacement is approximately the same, but the angular velocity is greater due to the pike. Hence the Yamahsita was assigned to the second position of complexity and the handspring vault to the third.

The handspring front has also been included in this analysis. This vault was performed by one subject only (JB) and while it can be put to no statistical tests, any patterns that are seen to develop over the other three vaults can be extrapolated to determine if they correspond to the results shown for this vault.

The handspring front was determined to be the most complex in terms of the angular momentum requirements in post-flight. It may appear at first sight that this vault would have the same post-flight angular momentum as the handspring, since it has three times the angular displacement, while the moment of inertia is reduced accordingly by tucking to approximately one third of that for the handspring. However the gymnast does not tuck immediately after leaving the horse, nor does she land in a tucked position. Therefore, in order to have the necessary angular velocity to complete the rotation she must necessarily have greater angular momentum.

When a comparison is made across the mean values of the three vaults (Tables 7 and 8 , pages 113 & 114) no general pattern emerges that can be considered as common to all vaults. Post-flight has been shown to be dependent upon pre-flight for each of the vaults, and each vault has a different post-flight requirement. Hence it was thought that variations between the individuals swamped the relationships between the vaults.

In order to achieve greater homogeneity of performance and a high level of skill, the results from the three consistently better performers (JB, JT and AA) were examined more closely. These nine vaults received performance criterion scores of greater than 0.31 and no vault was awarded a score of less than 8.2 points by the international judge.

These results (Tables 11 and 12) indicate that many of the measured characteristics of performance show markedly different values between the layout squat vault and the other two vaults. While other variables, horizontal velocity, take-off angle and vertical velocity at horse contact show very little variation across the vaults.

Vertical velocity at horse contact has been shown to be an important determinant for all three vaults and apparently the similar results found here have been achieved using different board take-off velocities and pre-flight displacements.

Angular velocity, average horizontal repulsive force and horizontal impulse are the only variables which show a consistent change across the three vaults.

These results were subject to Analysis of Variance and a

Table 11.

Pre-flight Means (and ranges) of the performance variables for vaulters JB, JT and AA.

		Layout Squat	Yamashita	Handspring
PRE-FLIGHT VARIABLES	T1 Duration (s)	0.23 (0.20 - 0.24)	0.28 (0.28 - 0.28)	0.29 (0.23 - 0.33)
	VX1 Horizontal Velocity ($m.s^{-1}$)	3.88 (3.70 - 4.07)	3.75 (3.56 - 3.91)	3.68 (3.45 - 3.89)
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.17 (3.00 - 3.39)	3.83 (3.74 - 4.00)	3.87 (3.63 - 4.03)
	TH1 Take-off Angle (degrees)	80.1 (76.2 - 85.1)	80.6 (75.2 - 87.9)	81.2 (75.5 - 85.6)
	X1 Horizontal Displacement (m)	0.89 (0.83 - 0.92)	1.09 (1.03 - 1.14)	1.07 (0.87 - 1.25)
	Z1 Vertical Displacement (m)	0.50 (0.39 - 0.57)	0.72 (0.66 - 0.74)	0.70 (0.63 - 0.80)
	THDOT Angular Velocity (degrees. s^{-1})	247 (219 - 269)	321 (296 - 339)	335 (297 - 357)
	TH2 Contact Angle (degrees)	190.4 (169.9 - 211.0)	146.0 (131.1 - 155.7)	153.4 (140.0 - 168.4)
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	1.08 (0.94 - 1.21)	1.06 (0.88 - 1.23)	0.99 (0.75 - 1.46)

Table 12.

Contact and post-flight means (and ranges) of the performance variables for vaulters JB, JT and AA.

		Layout Squat	Yamashita	Handspring
CONTACT VARIABLES	T2 Duration (s)	0.19 (0.18 - 0.21)	0.24 (0.23 - 0.26)	0.26 (0.24 - 0.29)
	X2 Horizontal Displacement (m)	0.58 (0.56 - 0.62)	0.70 (0.61 - 0.77)	0.69 (0.66 - 0.72)
	Z2 Vertical Displacement (m)	0.26 (0.23 - 0.31)	0.34 (0.32 - 0.38)	0.31 (0.24 - 0.39)
	FX1 Average Horizontal Compressive Force (N/body weight)	-1.25 (1.09 - 1.36)	-0.93 (0.90 - 1.20)	-0.98 (0.77 - 1.17)
	FZ1 Average Vertical Compressive Force (N/body weight)	2.34 (1.76 - 2.90)	1.50 (0.88 - 1.82)	1.47 (1.03 - 1.70)
	FX2 Average Horizontal Repulsive Force (N/body weight)	-0.13 (0.03 - 0.19)	-0.22 (0.15 - 0.33)	-0.30 (0.21 - 0.42)
	FZ2 Average Vertical Repulsive Force (N/body weight)	0.79 (0.74 - 0.82)	1.05 (0.96 - 1.22)	0.88 (0.79 - 0.96)
	IX Horizontal Impulse (N.s/body mass)	-0.89 (0.66 - 1.22)	-1.09 (0.81 - 1.31)	-1.28 (1.09 - 1.52)
	IZ Vertical Impulse (N.s/body mass)	2.03 (1.66 - 2.27)	2.72 (2.49 - 2.94)	2.60 (2.48 - 2.81)
POST-FLIGHT VARIABLES	XFL Horizontal Displacement (m)	1.60 (1.50 - 1.70)	1.65 (1.63 - 1.68)	1.32 (1.17 - 1.49)
	ZFL Vertical Displacement (m)	0.07 (0.04 - 0.09)	0.11 (0.08 - 0.13)	0.06 (0.03 - 0.11)

significant difference between the groups was found on all those expected, except duration of pre-flight, average horizontal repulsive force and horizontal impulse. Variables which show a significant difference have been indicated in Tables 11 and 12.

The layout squat vault has been performed with a lower vertical velocity at take-off, less horizontal and vertical displacement, and a lower angular velocity and contact angle than the other two vaults, while maintaining vertical velocity at contact.

The low contact angle (190.4°) enables the gymnasts to be in a good position to exert the force necessary to reverse the angular momentum. The larger turning effect of the vertical reaction force was due to the greater horizontal distance between the centre of gravity and the hand, as previously shown in Figure 27 (page 118). This low contact angle is the consequence of the combined effects of low angular velocity and short pre-flight.

The vertical compressive force is greater for this vault than the other two and will not only produce a greater turning effect, but will also lead to a greater gain in height, which is necessary since pre-flight vertical displacement is low.

Angular velocity and duration of horse contact are the only variables which show a consistent pattern of change across the three vaults. The angular velocity results are interesting since the vaults have been ranked according to angular momentum post-flight requirements. It appears that the mean angular velocity results reflect the pre-flight angular momentum. This is not unexpected since the same three subjects were used in the calculations and they had very similar body configurations over the frames which the calculations were made. Pre-flight angular velocity then is an important determinant of post-flight angular momentum for these vaults.

The handspring front vault has an even greater angular momentum requirement in post-flight, the extrapolation of this pattern of change would lead to the conclusion that pre-flight angular velocity should be greater in this vault than in any other. The angular velocity results for JB over the four ranked vaults are shown in Figure 35. From this it appears that the pattern of change is not continued to incorporate the more complex vault. However results for vault JBHSF indicate that she has successfully used the staircase effect between pre-flight and contact (VZ2 = $1.95 m.s^{-1}$, VZ3 = $2.11 m.s^{-1}$) to produce a greater vertical displacement in post-flight in order to be able to complete the rotation.

When post-flight displacement results are compared for the handspring and handspring front, both performed by JB a large difference can be observed.

Table 13.

Post-flight displacement

	XFL (m)	ZFL (m)
JBH	1.49	0.11
JBHSF	1.98	0.23

Hence it appears that there may be a limit to the amount of angular momentum that a gymnast can generate at take-off and that once this limit has been reached, more complex vaults will make greater use of the staircase effect in order to be able to successfully complete the vault.

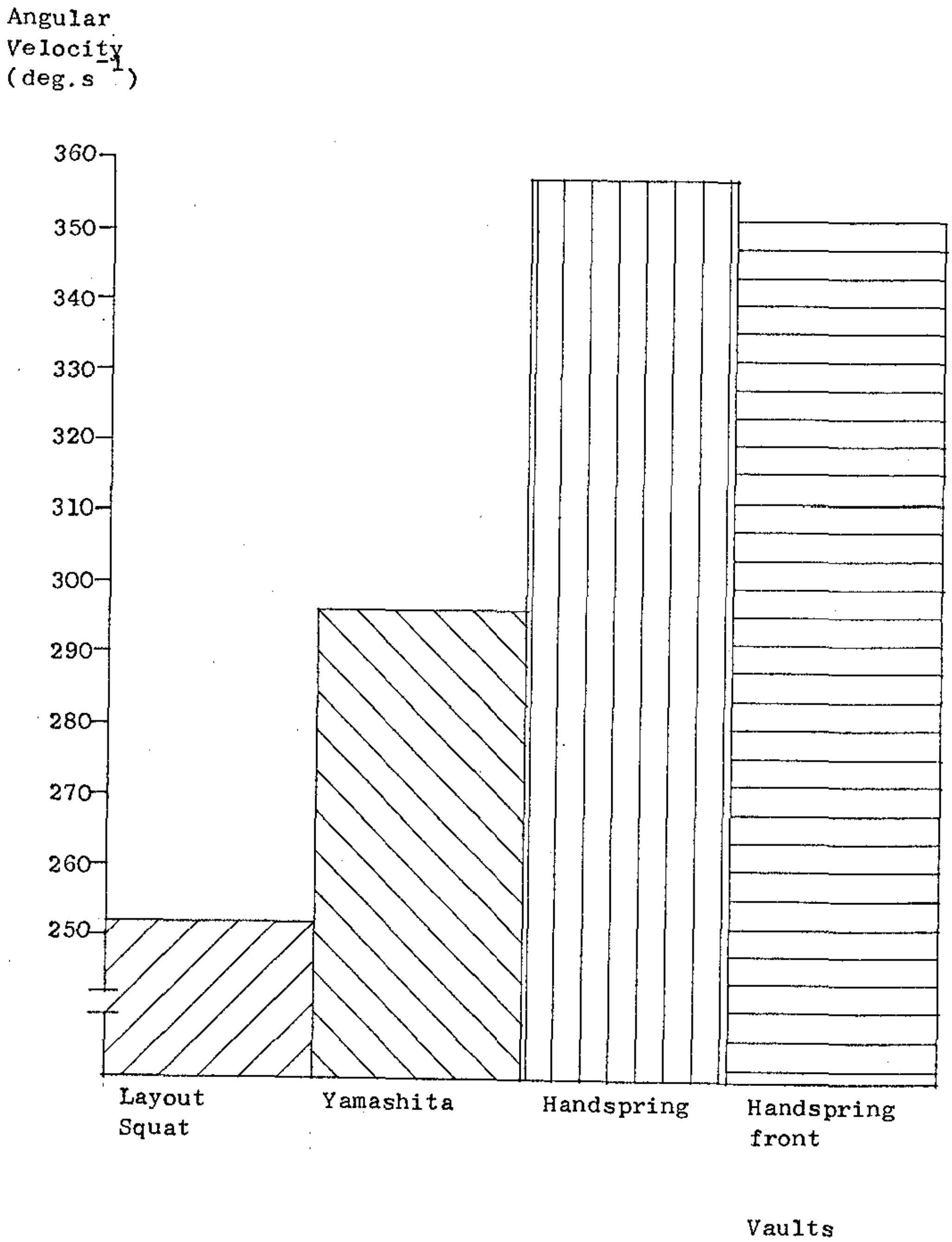


Figure 35. Angular velocity vs. vault: JB.

CHAPTER 5

SUMMARY, DISCUSSION AND CONCLUSIONS

CHAPTER 5: SUMMARY, DISCUSSION AND CONCLUSIONS.

SUMMARY.

The biomechanical characteristics of the layout squat, handspring and Yamashita vaults have been described and observations made concerning the effects of the performance in the initial phases on post-flight. These results have been used to produce predictive equations for post-flight from the two preceding phases. The dependence of post-flight upon pre-flight performance for all three vaults, and the dependence of contact behaviour on pre-flight for the layout squat and handspring vaults was confirmed.

Application of these equations to other performances has been shown to be good for the handspring and Yamashita vaults, but not for the layout squat vault. However mechanical principles indicating the importance of the staircase effect in producing a good performance held true for all vaults.

The results from the best performers (from Experiment 1) have also been analysed, over all vaults, to determine consistencies between their initial phases. The complexity of the successful vault has been seen to be explained by the angular momentum requirements of post-flight.

From a homogeneous group of nine highly skilled gymnasts of International, National and Regional levels, aged 14 to 21 years, kinematic data was gathered on all subjects and kinetic data on the six subjects in Experiment 1.

Answere were sought to the following questions:

1) What are the biodynamic characteristics of the pre-flight, contact and post-flight phases of a vault?
2) Which of the biodynamic characteristics are most instrumental in producing the best post-flight?
3) In what way are the performance variables of contact due to the pre-flight and to what extent do they account for post-flight behaviour?
4) If the pre-flight characteristics are controlled to conform with selected criteria can the resultant post-flight be accurately predicted?
5) If post-flight characteristics are controlled to conform with selected criteria, i.e. different types of vaults are performed, can patterns of change be shown across the initial phases of the related vaults?

CONCLUSIONS

On the basis of the results obtained and within the limitations of the techniques used, the following conclusions are drawn:

1a) The biodynamic characteristics of pre-flight are determined by the necessity to have a high vertical velocity at the end of pre-flight.

b) The biodynamic characteristics of contact reflect the necessity to change the angular momentum and to gain lift from the horse.

c) The biodynamic characteristics of post-flight are largely determined by the need to gain sufficient height, without undue loss of distance, to complete the rotation required for the specific vault.

2) For the three vaults studied the post-flight performance was found to be dependent upon pre-flight.

a) For the layout squat vault a short duration of pre-flight (down to 0.17s) a high contact angle and vertical velocity are instrumental in producing the best post-flight.

b) For the handspring vault the characteristics of greatest importance in producing a good post-flight were a high vertical velocity at horse contact, a low take-off angle and a high angular velocity.

c) Characteristics of importance in producing a good result for the Yamashita vault were horizontal pre-flight displacement which was not short (less than 1m), a high vertical velocity at horse contact and a low take-off angle.

3a) For the layout squat vault duration of contact could account for almost all of the variation shown in post-flight performance. However it was itself determined by the pre-flight performance.

b) The contact variables which produced a good result for the handspring vault, short duration and small vertical impulse, were also found to be dependent upon pre-flight performance.

c) The important characteristics of contact for the Yamashita, horizontal and vertical impulse and compressive forces could not be shown to be dependent upon pre-flight performance, due to the small number of subjects. However because information from pre-flight variables permit the prediction of post-flight (accounting for 99.3% of the variance) it was concluded, although with reservations because of the small number of subjects contributing data, that a relationship did exist between the pre-flight and contact phases for the Yamashita.

4) When pre-flight characteristics are controlled to conform with selected criteria and performance variables are close to those shown by the subjects in the initial experiment, the resultant post-flight displacement can be predicted with reasonable accuracy.
5) When vaults are ranked according to the angular momentum of post-flight, angular velocity in pre-flight increases in magnitude up to a limit where the staircase effect between pre-flight and contact becomes more important.

DISCUSSION

The pre-flight phase.

Results indicate that a high vertical velocity at horse contact is an important post-flight determinant in all vaults. This has generally been achieved through a shorter duration of pre-flight. However for the Yamashita it was indicated that a larger horizontal displacement produced better post-flight performance.

Results from a study by Ferriter (1964) show pre-flight displacements ranging from 0.79 to 1.27m and duration from 0.19 to 0.35s. These ranges are very similar to those shown by the gymnasts in Experiment 1, where pre-flight displacement ranged from 0.87 to 1.32m and duration from 0.23 to 0.36s. However the take-off vertical velocity shows a large difference between the two groups. Ranging from 1.30 to 1.83m.s^{-1} in Ferriter's study and 3.63 to 4.03m.s^{-1} in this study. Hence it can be seen that these vaults were performed using different techniques where the subjects from this study mostly showed a constantly rising pre-flight and a positive vertical velocity at contact, where the higher velocity produced the better result. The subjects from Ferriter's study can be assumed to have a negative vertical velocity at horse contact since they would have reached the peak of their pre-flight trajectory before they contacted the horse. They all left the horse with a negative vertical velocity, therefore failing to gain any lift. Of course the requirements of vaulting at this time dictated that pre-flight and post-flight motion should be symmetrical about the horse. All but two of Ferriter's subjects exhibited a larger parabola of the centre of gravity in pre-flight than in post-flight, whereas the reverse situation was found to exist in this study. Therefore vertical velocity at horse contact can be seen to be not only determined by duration of pre-flight, but also by the resultant take-off velocity.

The vertical velocity at take-off was also less for gymnasts in a more recent study by Dainis (1979), with a range from 2.66 to 2.90m.s^{-1}. However the pre-flight trajectory was similar to that shown by the subjects in this study since vertical velocity at contact shows only slightly lower values in the range from -0.17 to 1.20m.s^{-1} compared with this study's 0.20 to 1.46m.s^{-1}. Dainis similarly concluded that post-flight performance was largely determined by this variable.

Conclusions drawn concerning the layout squat vault must similarly be placed in the wider context of opinions expressed by other authors.

The layout squat vault has been best performed here with a short duration of pre-flight (to a limit of 0.17s) and a high contact angle. The high contact angle would appear to conflict with opinions expressed by Hendershott (1974) and others (Bajin, 1971; Bollen, 1978). However Hendershott recommended that the formerly required contact angle of 45° was too high and that an angle of 30° produced a better post-flight performance. The highest contact angle in this study was only just greater than 10° above the horizontal. Therefore when placed in the wider realm of performance it can be seen that all these angles are low, the highest being 20° below that recommended by Hendershott. One may therefore assume that the optimum contact angle, for ensuring a good post-flight lies between the values of $10\text{-}30^{\circ}$ above the horizontal.

Concerning pre-flight performance of the Yamashita, the previous studies conducted on this vault (Vanis,1964; Hatano, 1976), could reach no conclusions with regard to the effect of pre-flight on post-flight. This was largely due to the great variation between individual performances. However results from this study indicate that at least up to a maximum of 1.14m, a greater horizontal displacement produces the better post-flight.

The contact phase.

Angular velocity during pre-flight has been considered by Dainis

(1979, 1980) to be an important determinant of duration of contact and post-flight performance in handspring vaults, since the initial compressive force will be high. This has been shown to be the case for handspring vaults in this study, but not for Yamashita vaults. Two of the better subjects JT and AG appeared to exert a greater force during the repulsive phase and thereby gain lift. This technique has also been recently found by Dainis (1981) in handspring vaults. The appearance of these two techniques warrants further investigation.

Horizontal contact forces for the layout squat have been recommended to be in a backwards direction (George, 1980; Hay, 1978; Hatano, 1976). No subject in this study showed a horizontal impulse in a backwards direction and only one subject showed a backwards component of this force during the repulsive phase. This situation probably occurs due to the low contact angle shown by these subjects. The low angle, which is the result of a low angular momentum, will give a greater horizontal distance from the centre of gravity to the wrists, so increasing the turning effect of the vertical reaction vector. Thus not only will the gymnasts have less angular momentum to reverse but will also be in a better position to do so.

<u>Differences between the types of vaults</u>

When comparing performances for the layout squat, handspring and Yamashita vaults Hatano (1976) was unable to discern any difference between the performance of the gymnasts for the initial phases. This was due to the large between-performer variation shown in the study. However large differences have been shown in this study between the layout squat and both the handspring and Yamashita vaults. Patterns of change were found across all three vaults for pre-flight angular velocity and duration of contact. Dainis (1981) has suggested that there may be a limit to the amount of rotation that can be initiated at take-off. Such a limit was found for subject JB since when she performed the handspring front vault the pre-flight angular velocity did not show the expected increase from 357 $deg.s^{-1}$. Rather she used the staircase effect to greater advantage in gaining more lift from the horse than she had shown for the handspring. This increased use of the staircase effect was also recommended by Hay (1978) in the performance of the Hecht vault where an increase in angular momentum would increase the chances of the gymnast's feet hitting the horse. While the application of the greater use of the staircase effect has been deemed necessary for a different reason, the principle is the same, in that where angular momentum can not be increased then the gymnast will require a longer duration of post-flight in order to complete the rotation successfully. This longer duration is brought about by a greater vertical velocity upon leaving the horse, due to the staircase effect between pre-flight and contact.

RECOMMENDATIONS

The following recommendations for future study are made:

1) For many of the important pre-flight variables the best results were found to be produced from the end of the range, therefore no upper (or perhaps lower) limit could be placed on optimum performance. It is recommended that in order to determine such limits a study be conducted which alters the pre-flight horizontal displacement to above and below the values recorded during this study.

2) The different techniques used to gain lift from the horse need further investigation to determine which produces the best result. While pre-flight angular velocity has been shown to determine contact for the rebound technique, no firm statements can be made about the technique which shows the large vertical repulsive force. Gymnasts could be grouped according to the technique they use and comparisons made along similar lines to those made in this study.

SUMMARY OF CONCLUSIONS.

1) The optimum characteristics of performance in the early phases of a vault are specific to each vault. As these characteristics determine post-flight performance more attention should be paid to their precise execution by gymnasts and coaches than has previously been recommended.

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APPENDIX A.

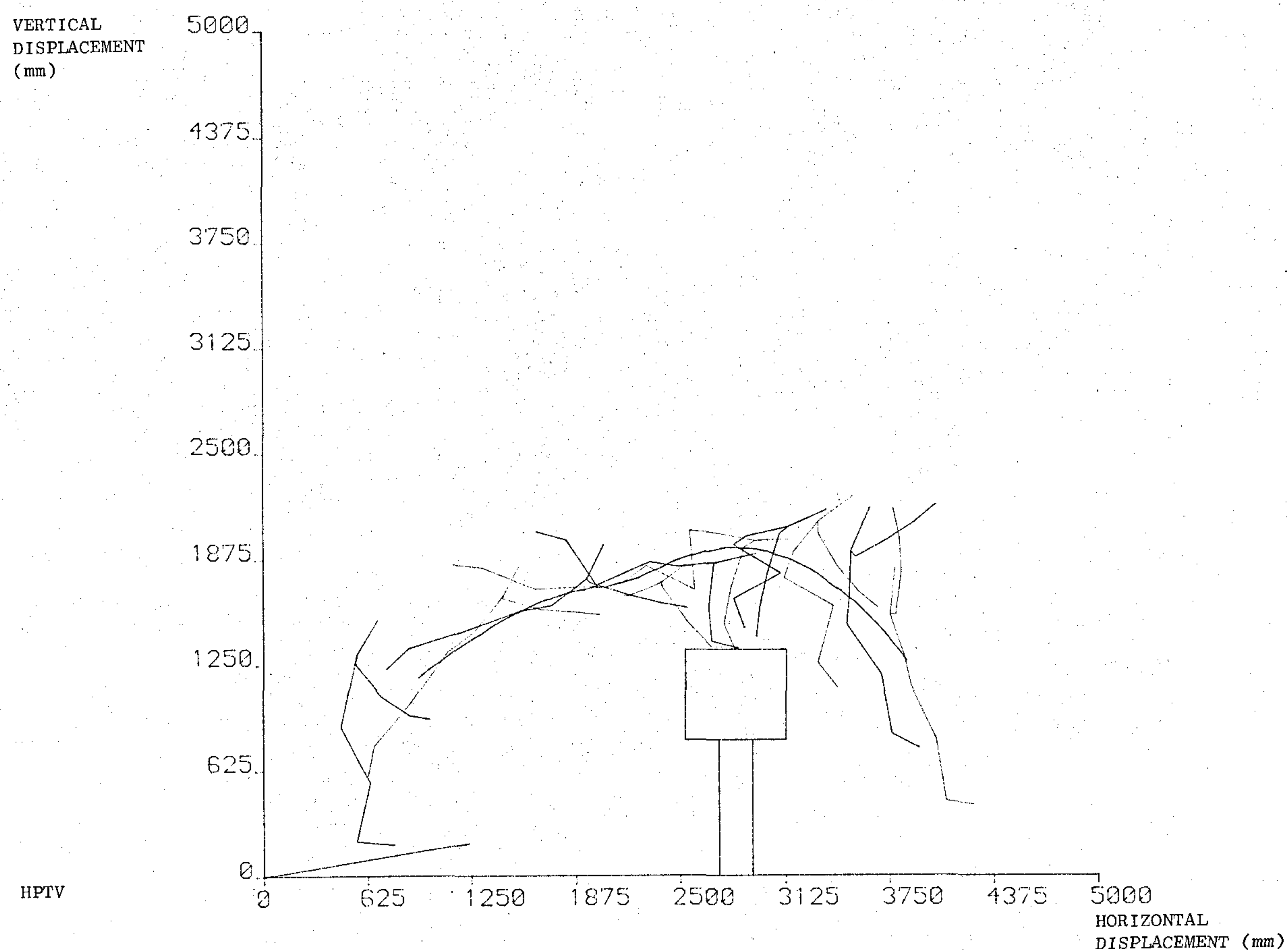
Graphic display of kinematic data.

Note: Line diagrams drafted for every seventh frame of the kinematic data for all subjects and all vaults are presented, together with the calculated paths of the subjects' centre of gravity for the pre-flight, contact and post-flight phases.

The initials of the subject and of the vault represented (TV = layout squat, H = handspring, Y = Yamashita, HSF = handspring front) are recorded in the left lower corner of each graph. True vertical and horizontal displacements (in mm) are shown on the two axes.

For greater clarity each frame is drawn alternately in red or green ink.

The accuracy of the basic data and calculations may be judged from these diagrams.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3125
3750
4375
5000
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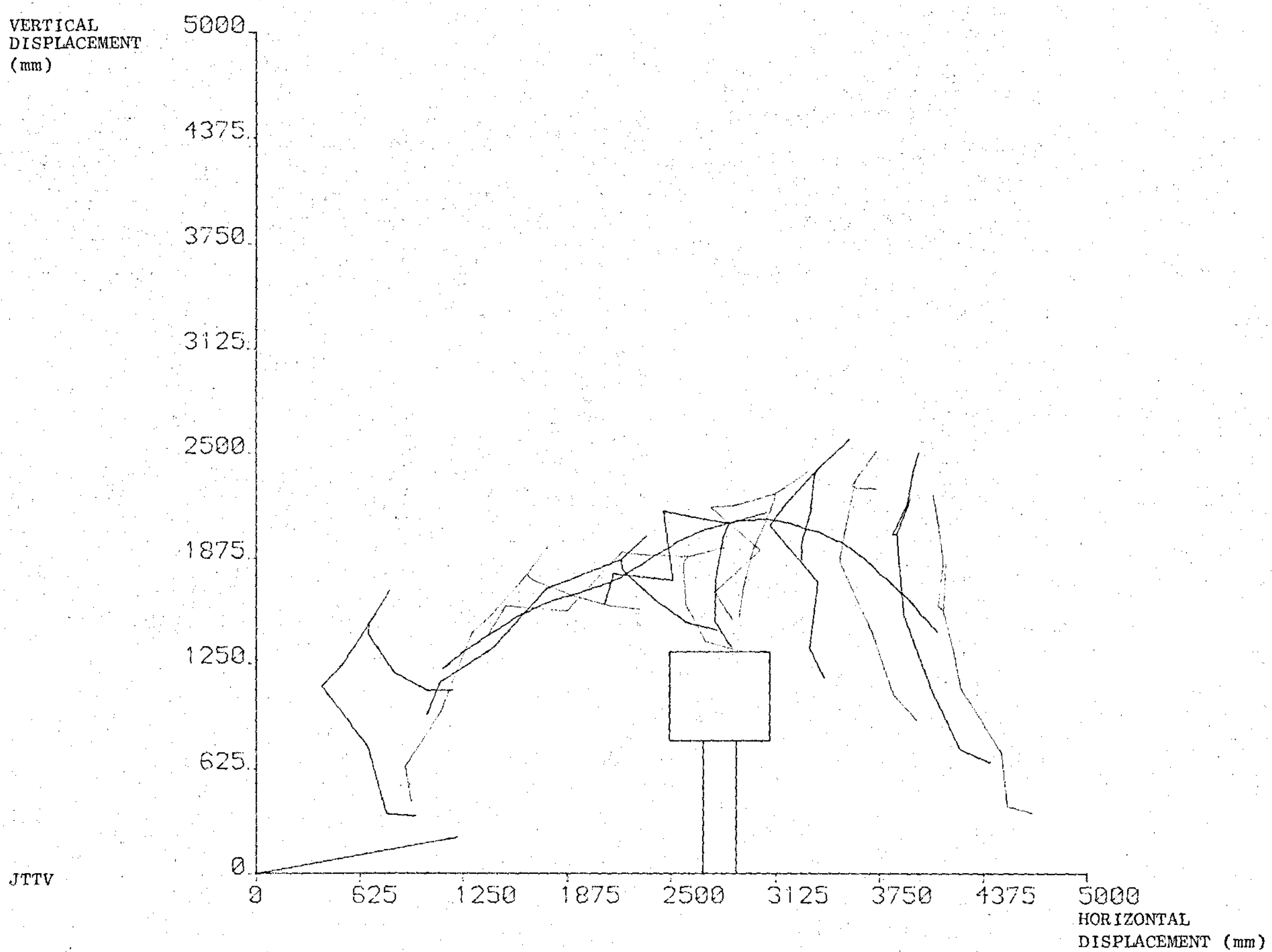
DISPLACEMENT (mm)
HPTV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4375
5000
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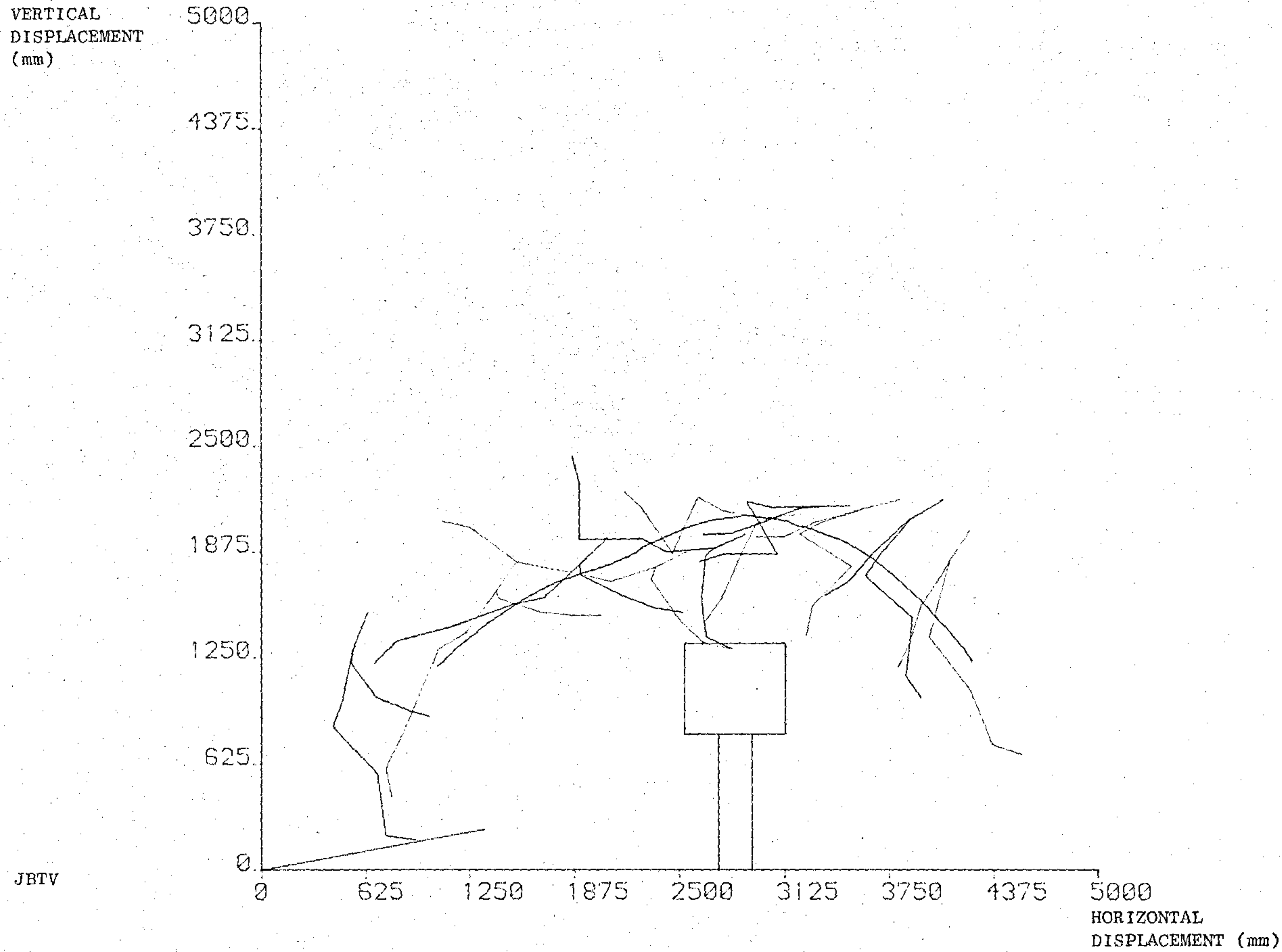
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3750
4375
5000
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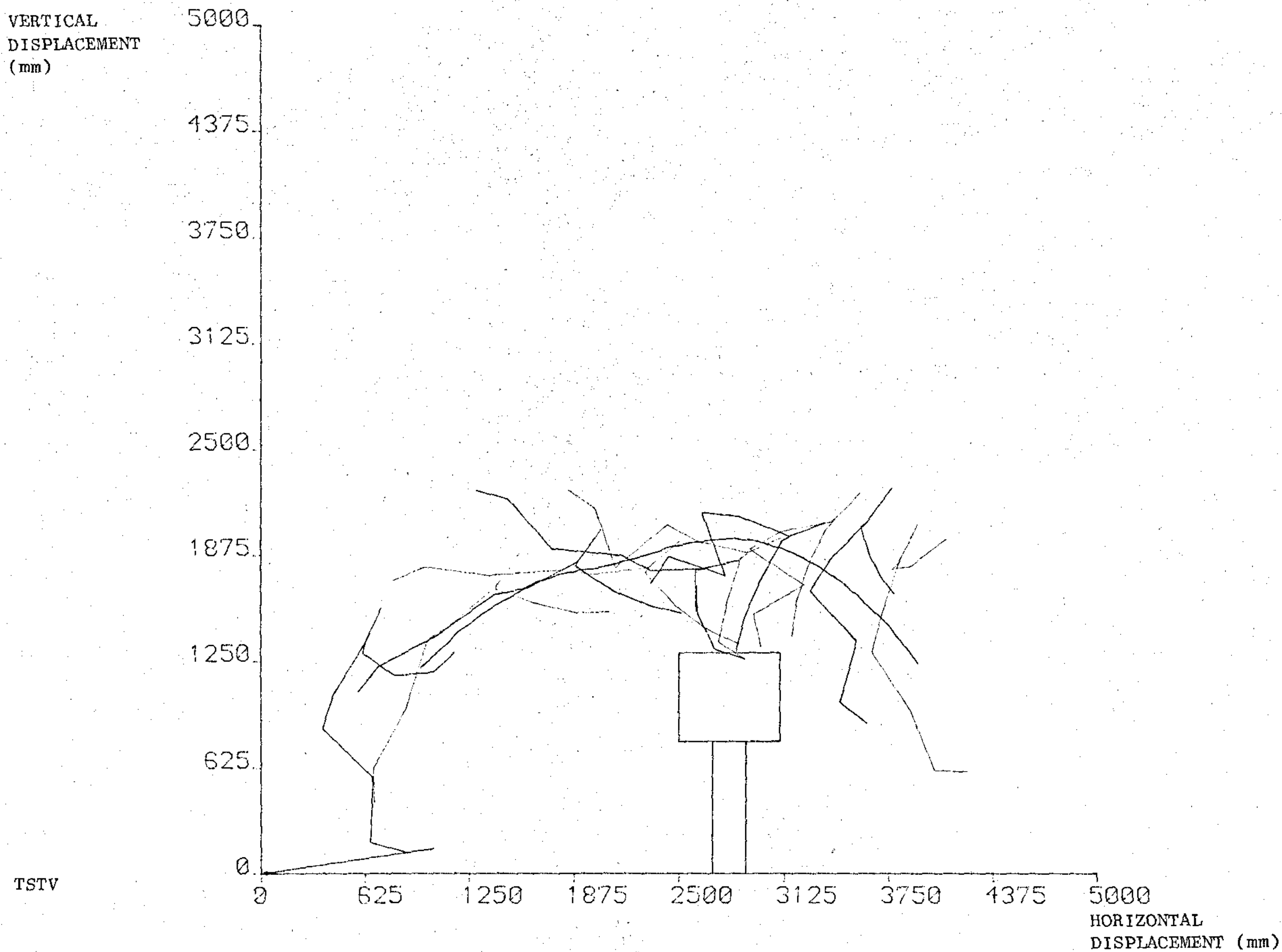
DISPLACEMENT (mm)
JBTV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4375
5000
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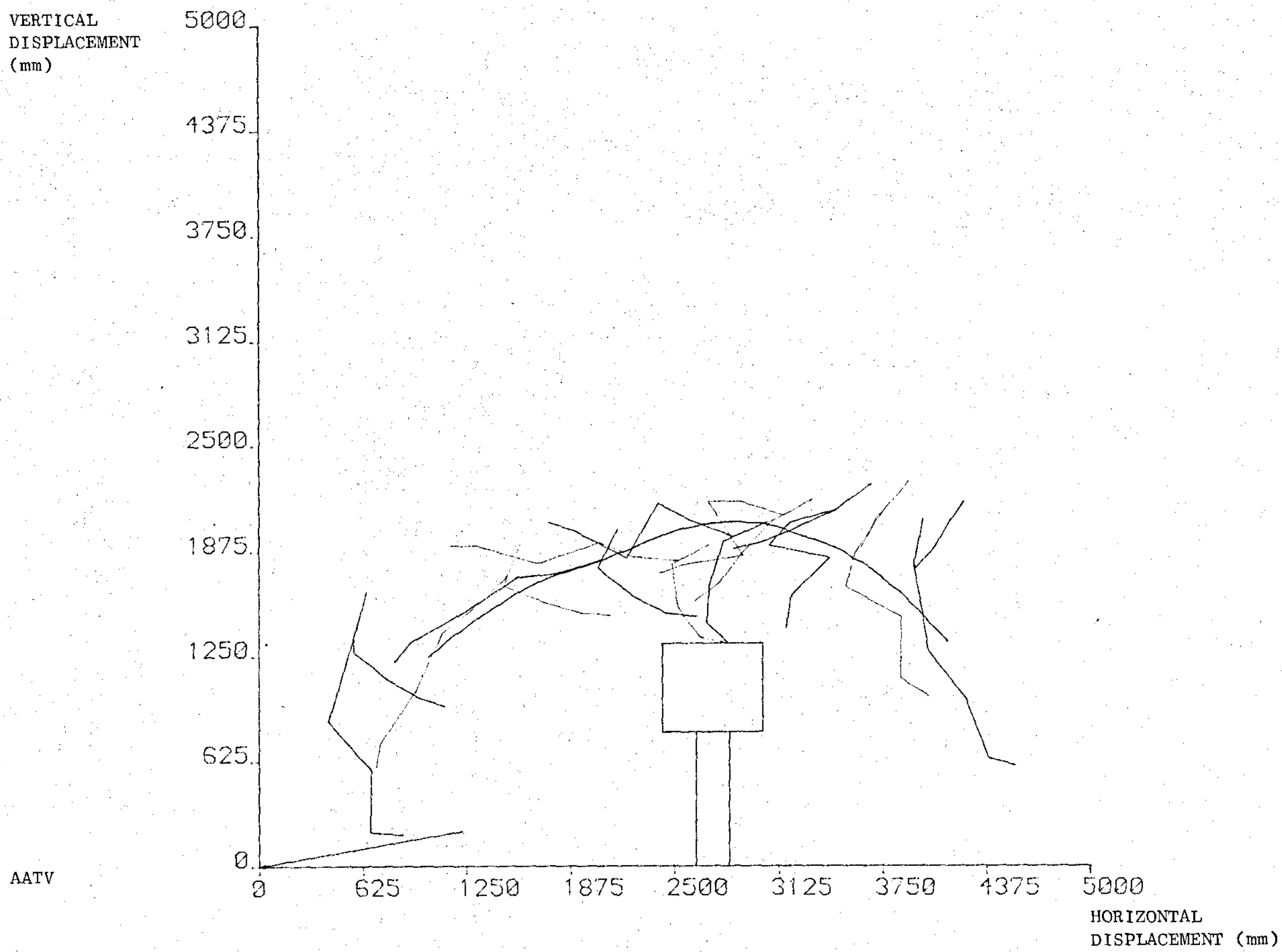
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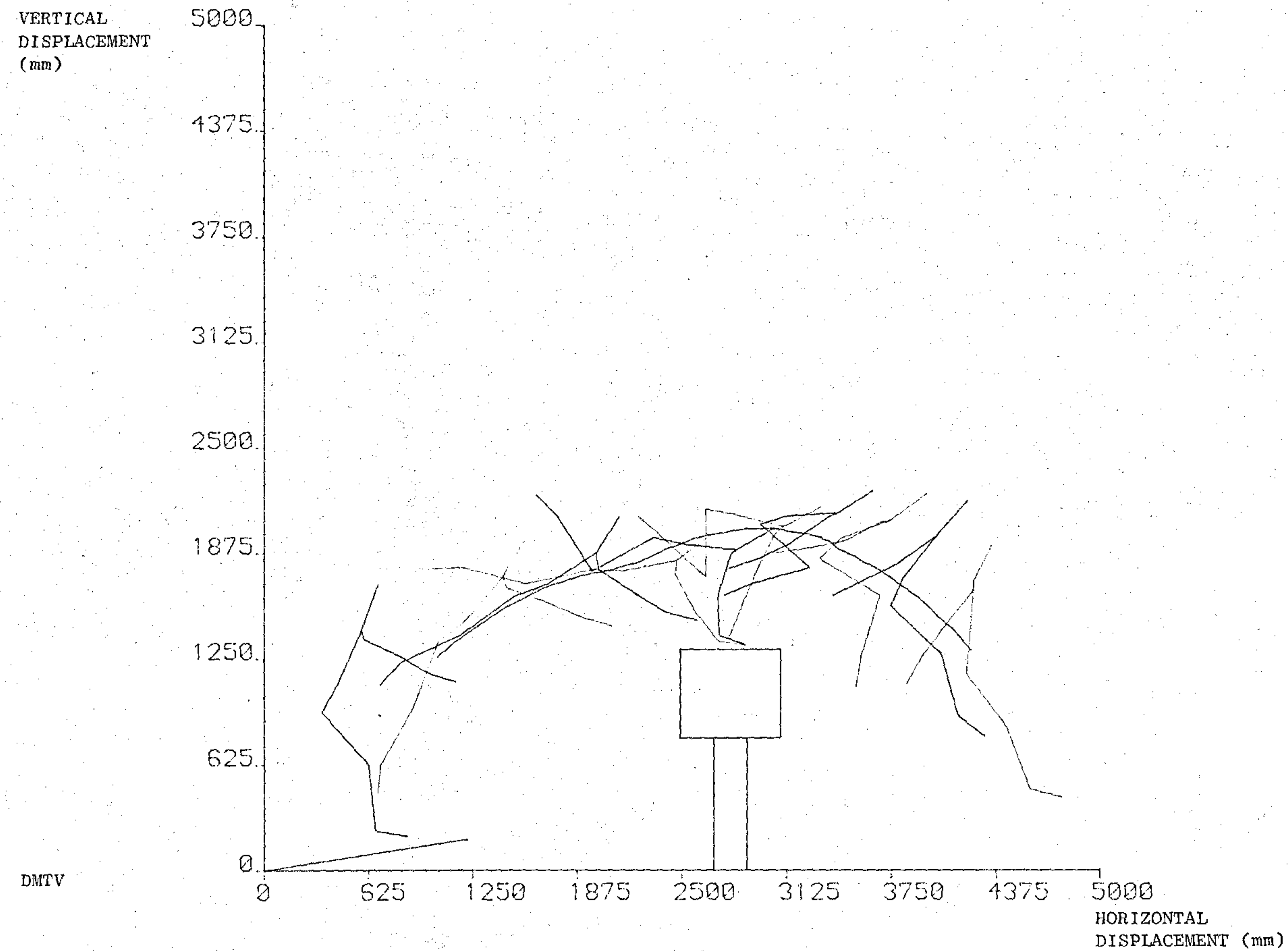
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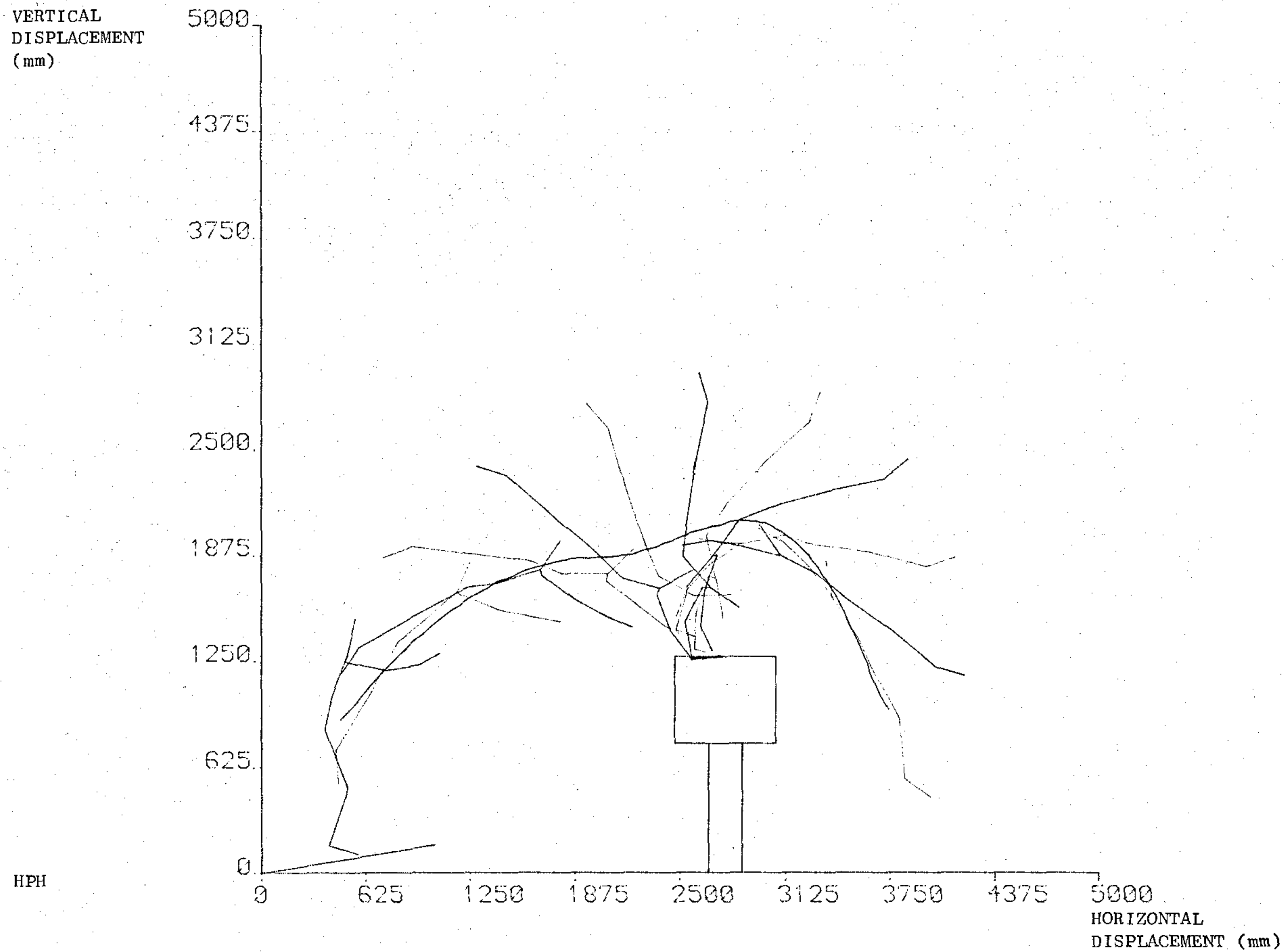

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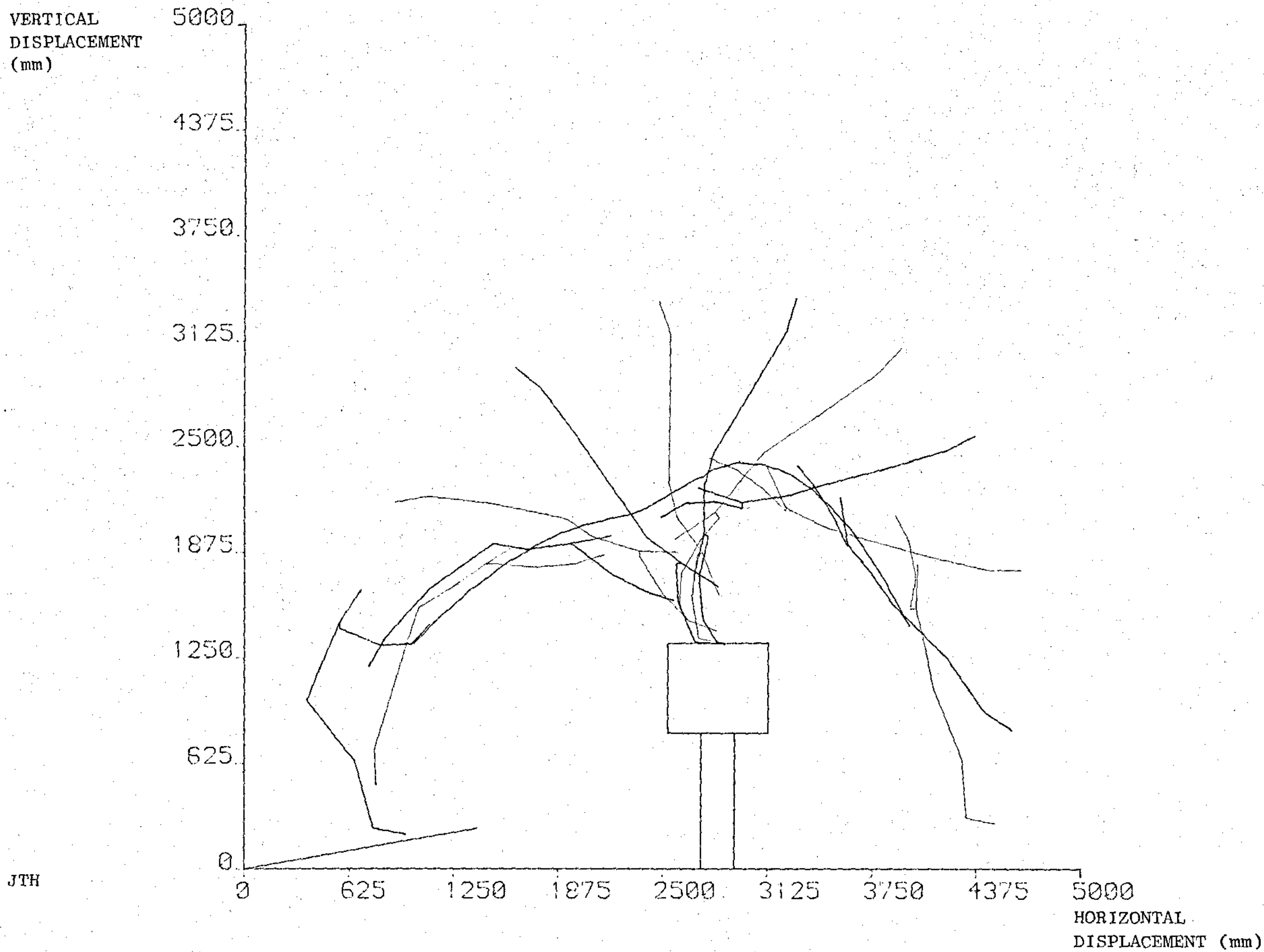
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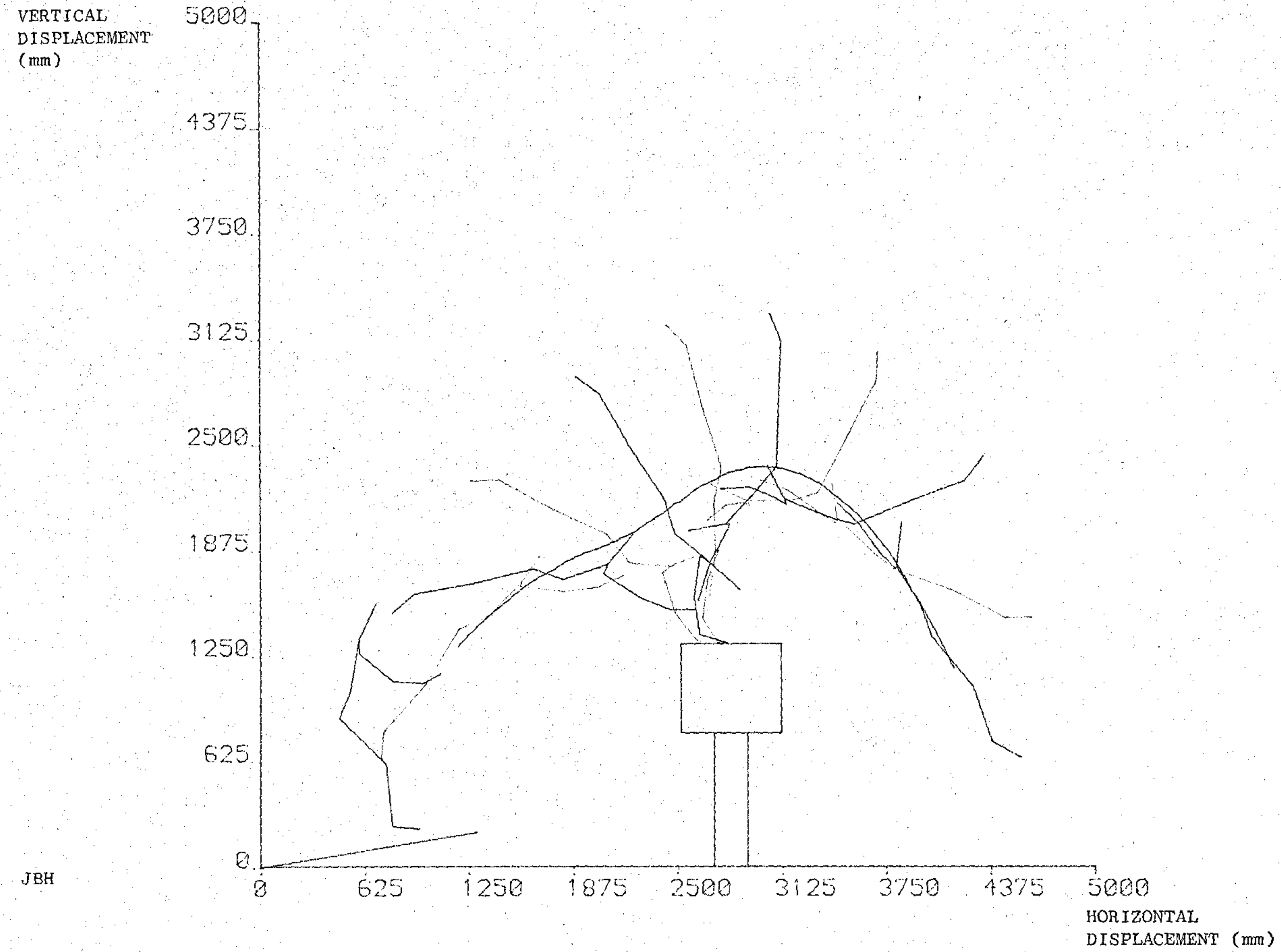
DISPLACEMENT (mm)
JTH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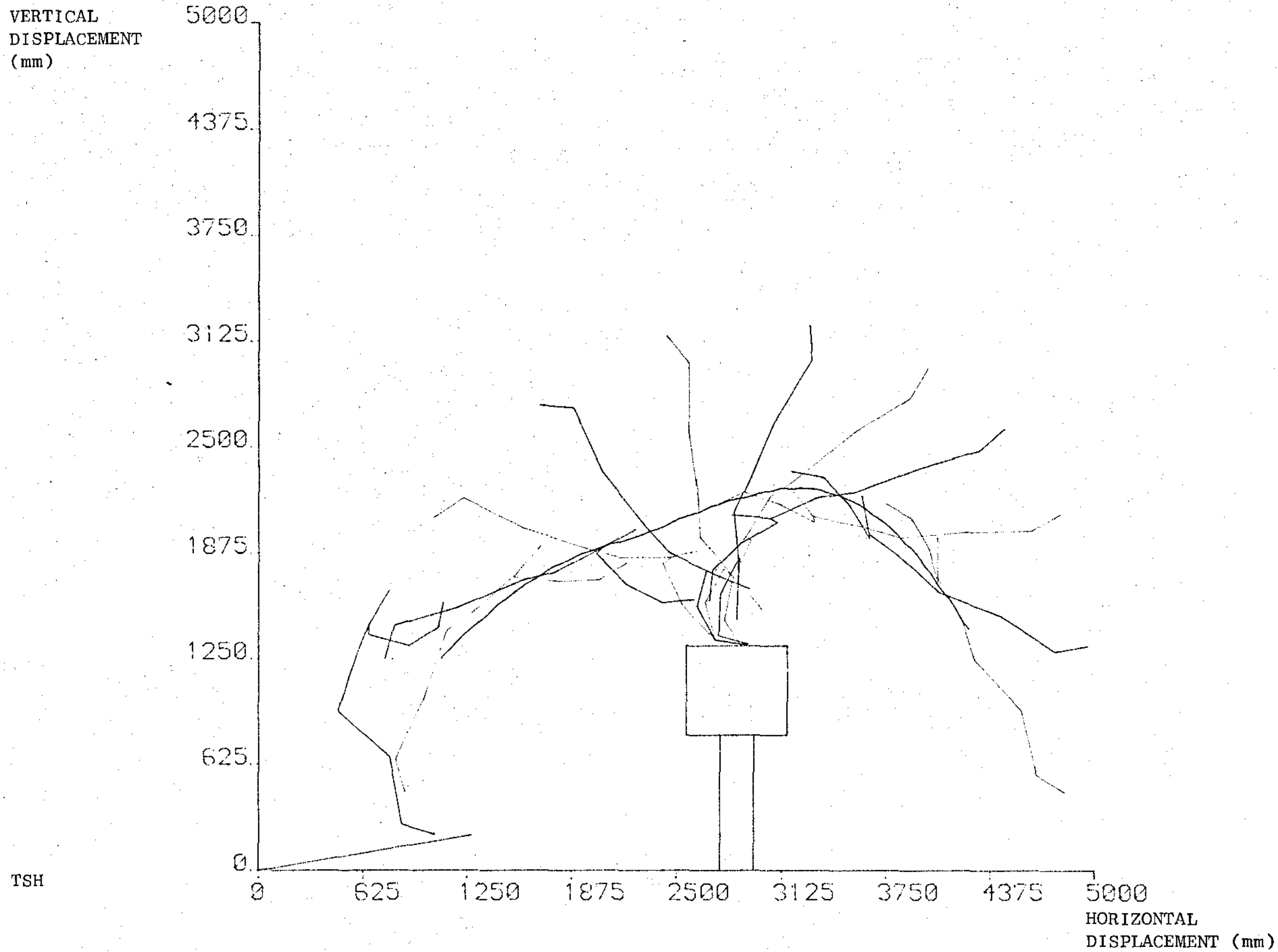
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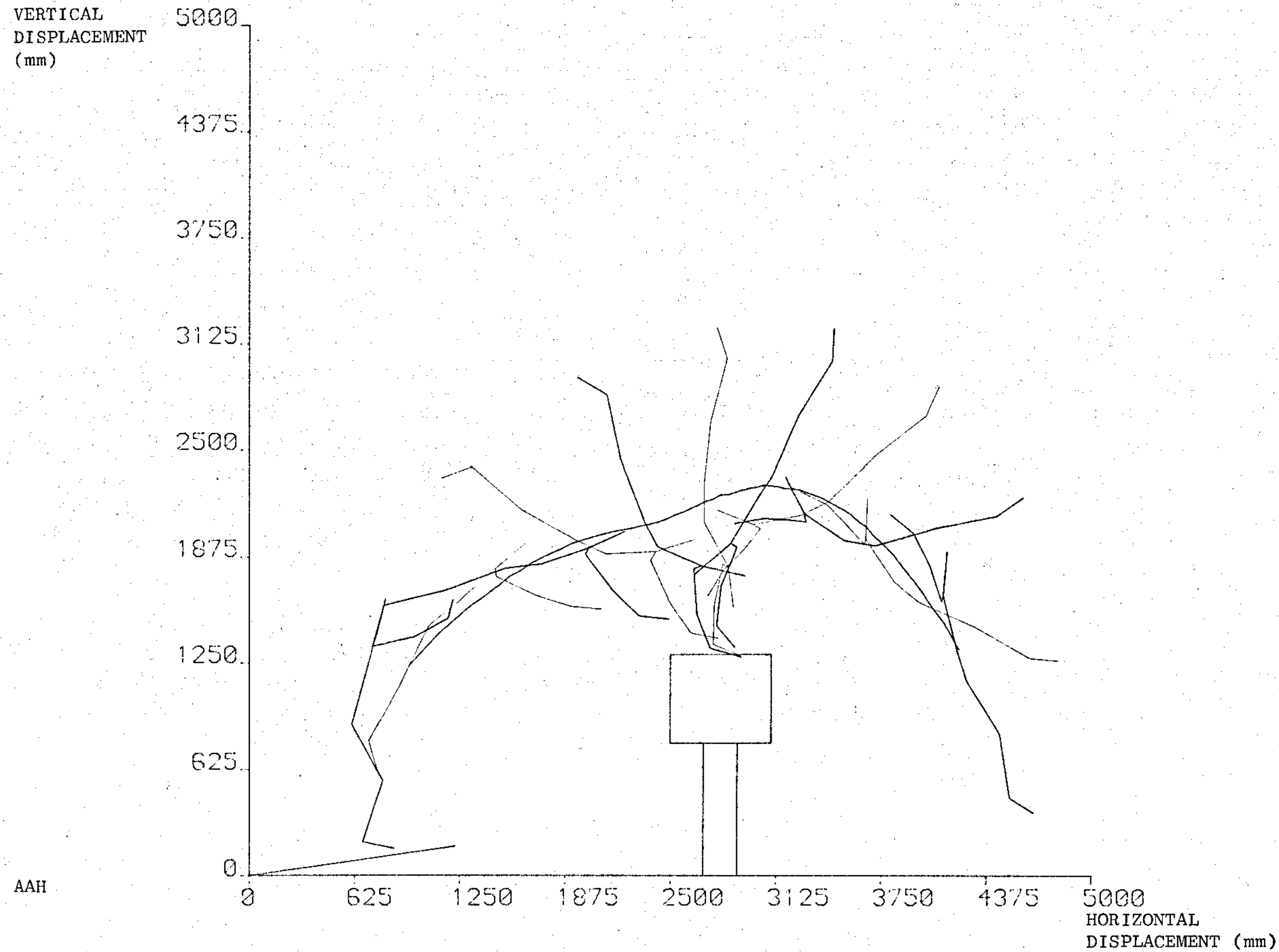
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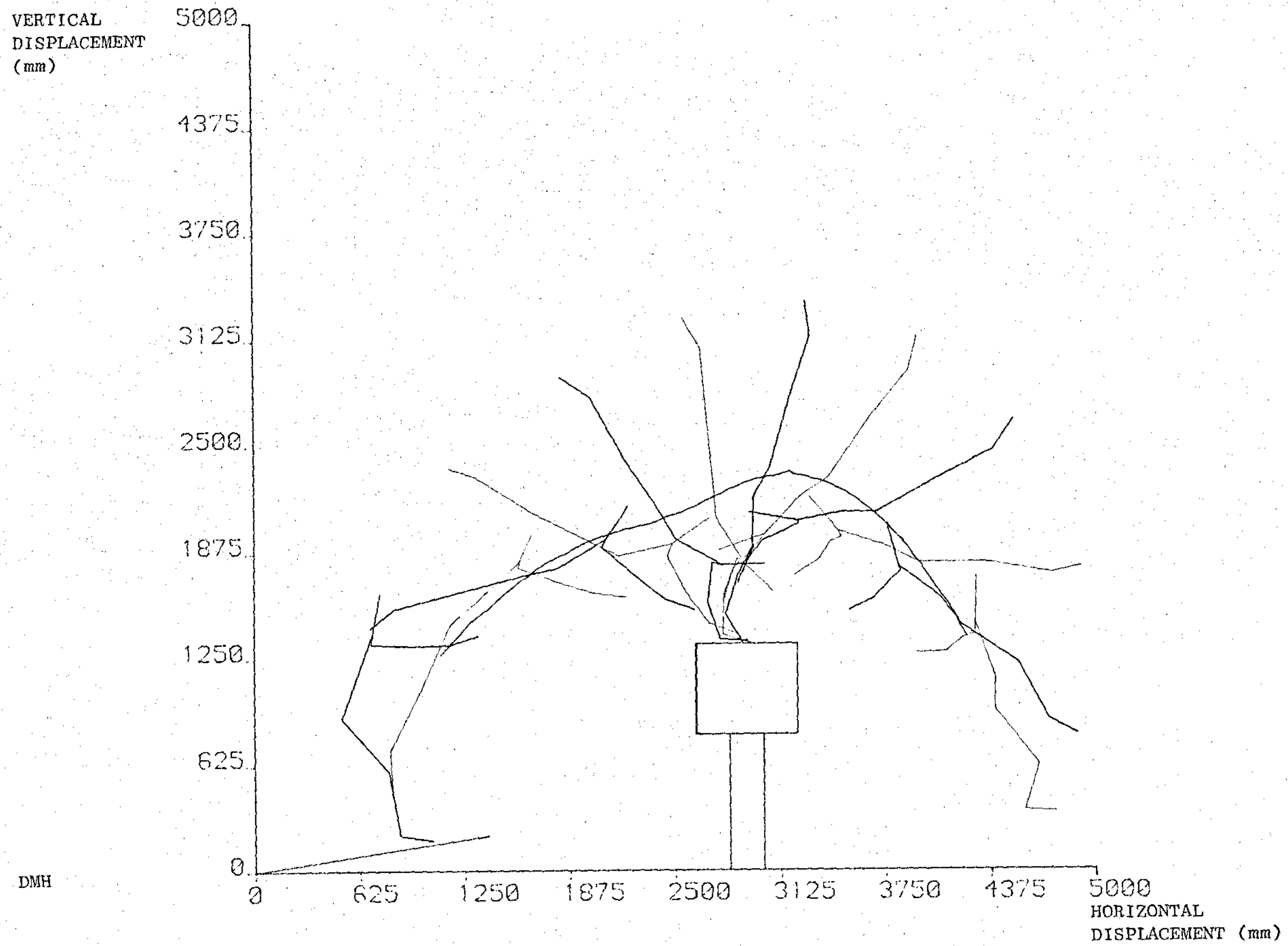
3125
3750
4375
5000
HORIZONTAL
DISPLACEMENT (mm)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4375
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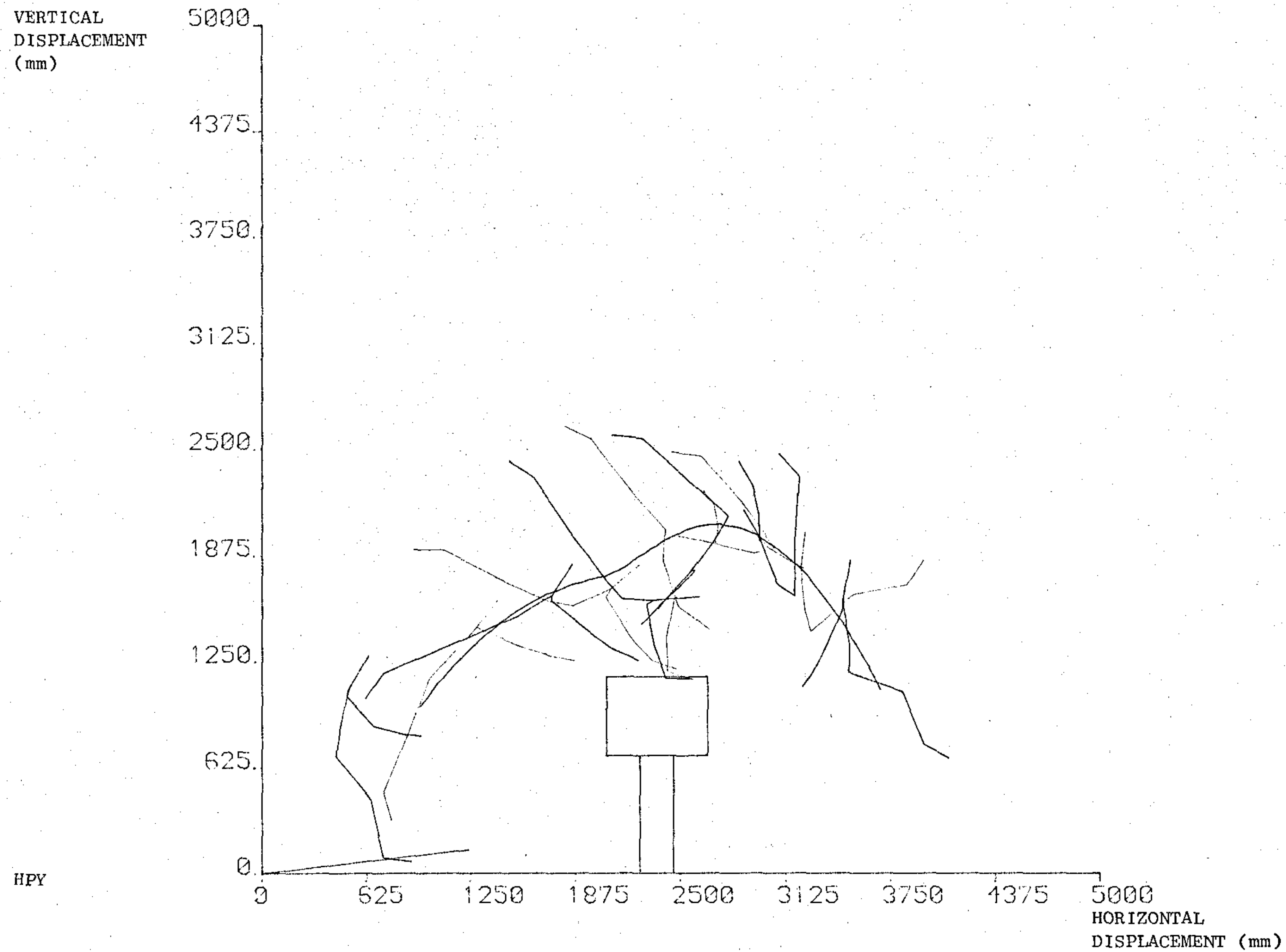
DISPLACEMENT (mm)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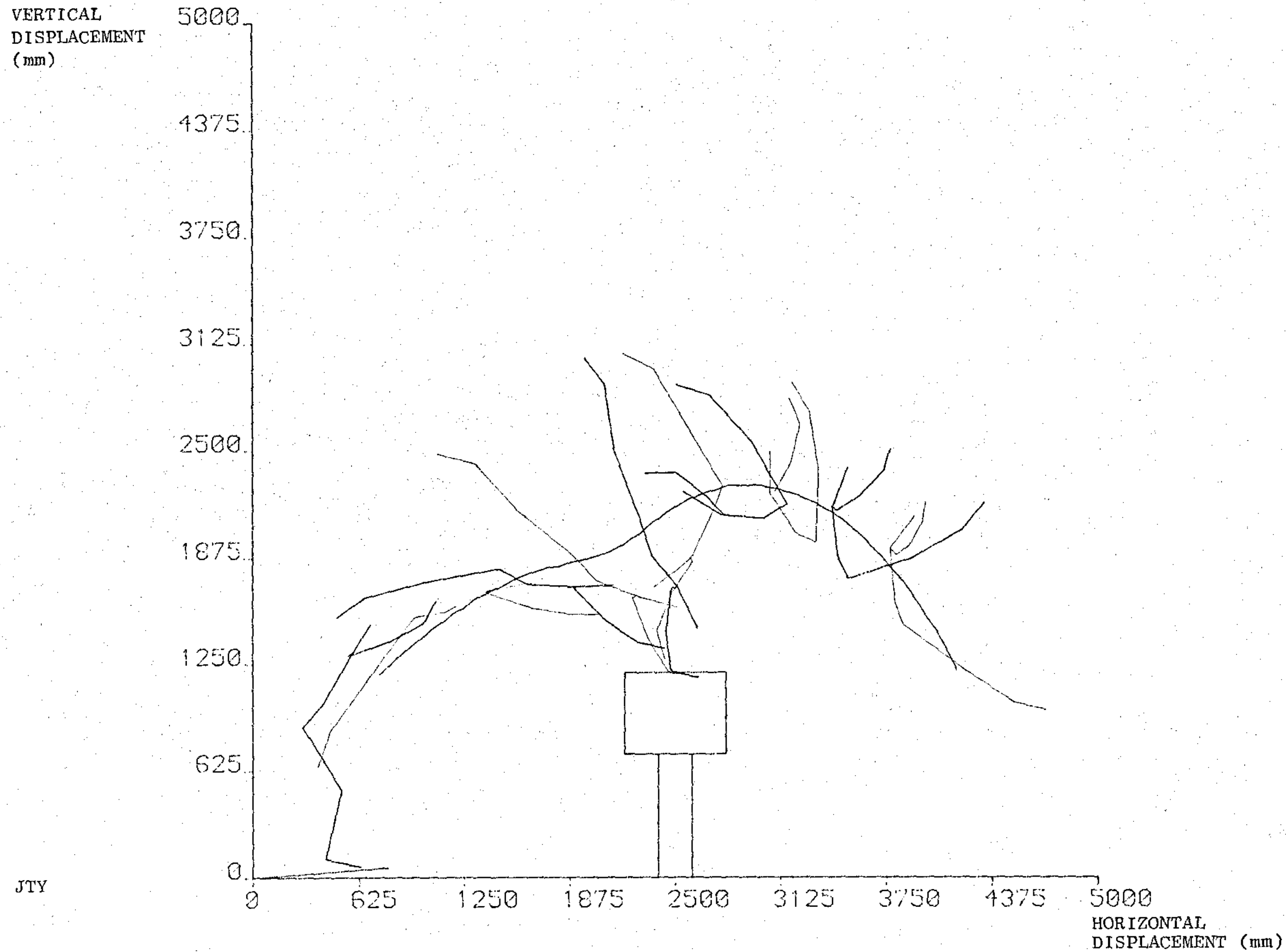

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5000
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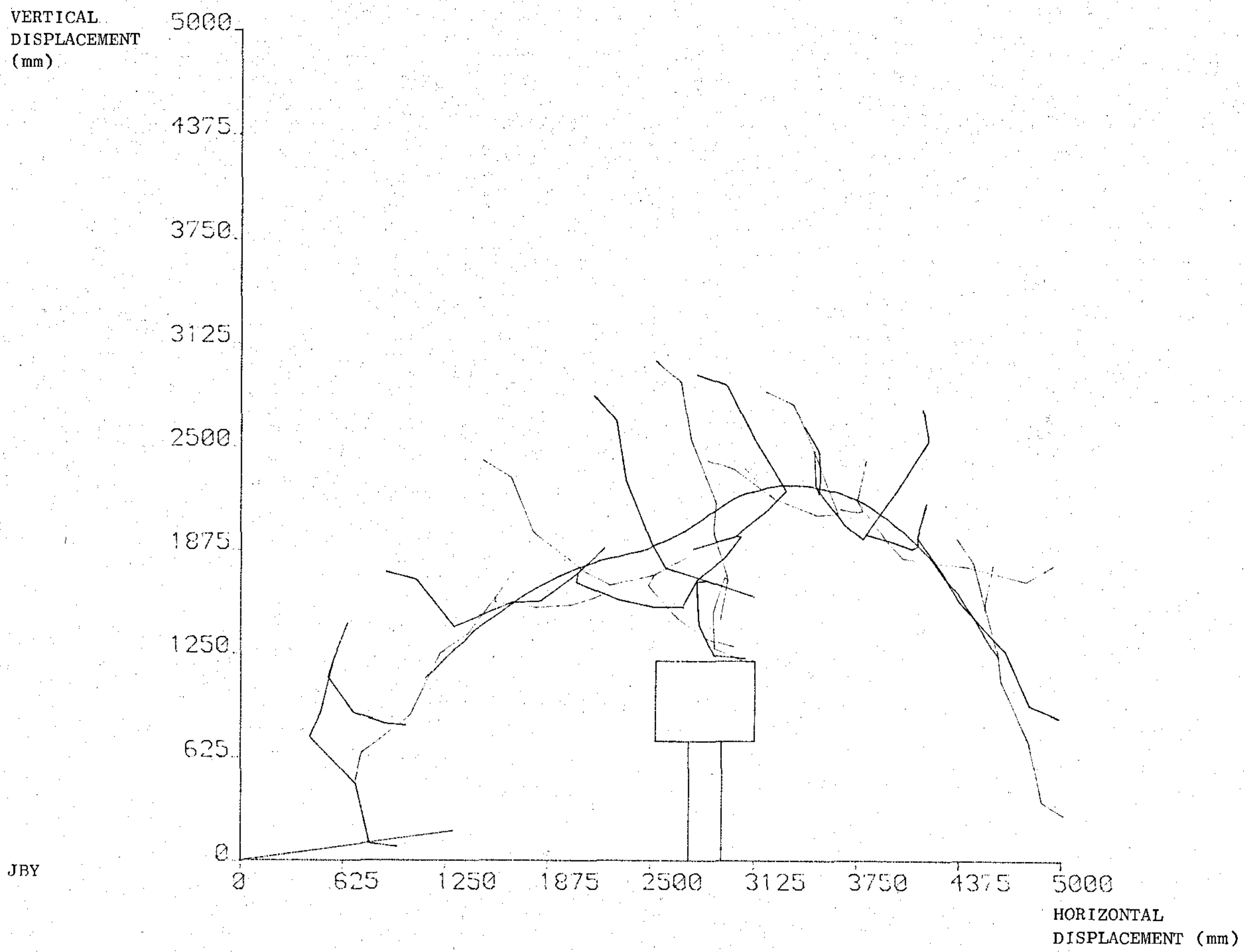
JTY



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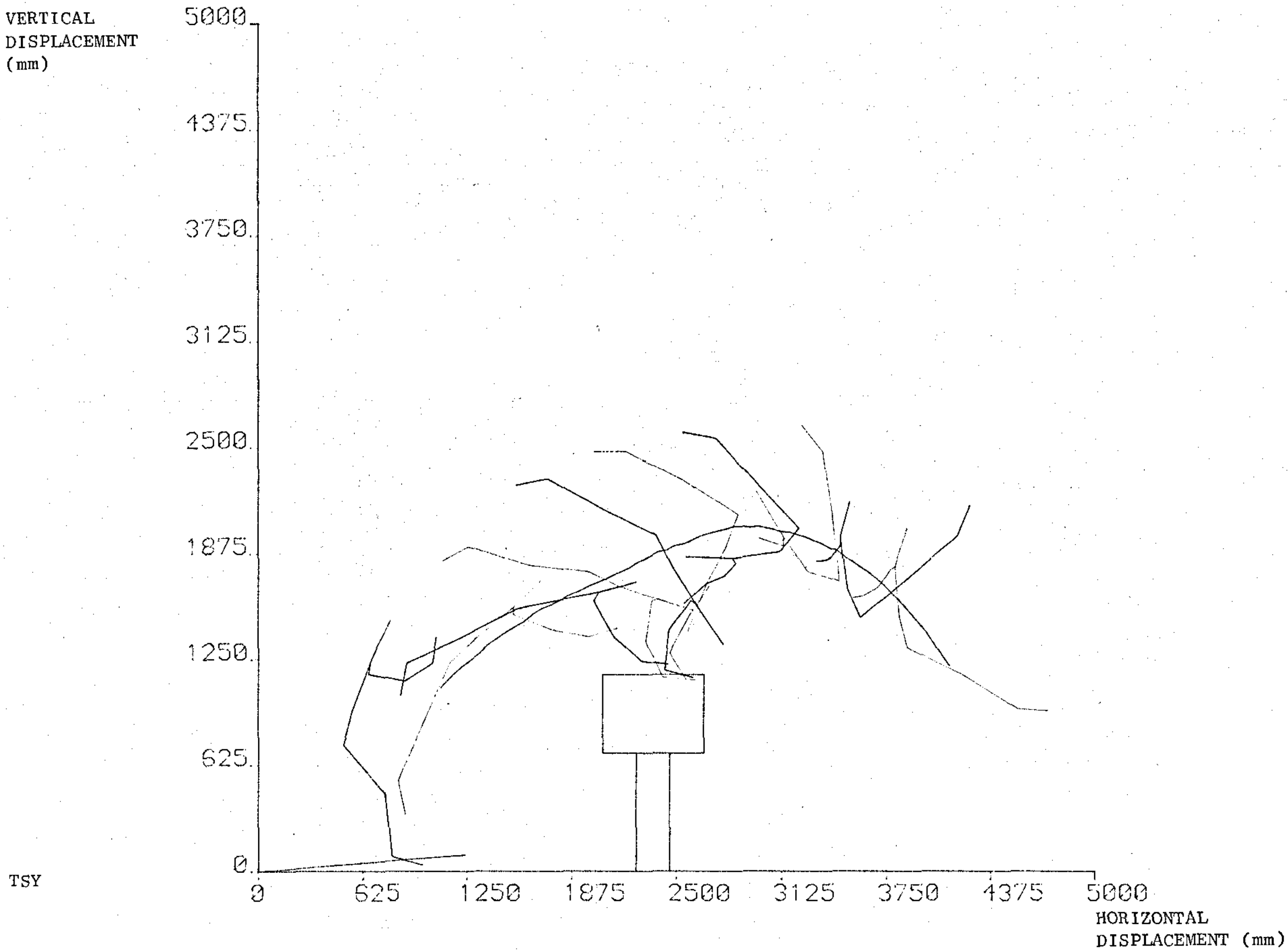
DISPLACEMENT (mm)
JBY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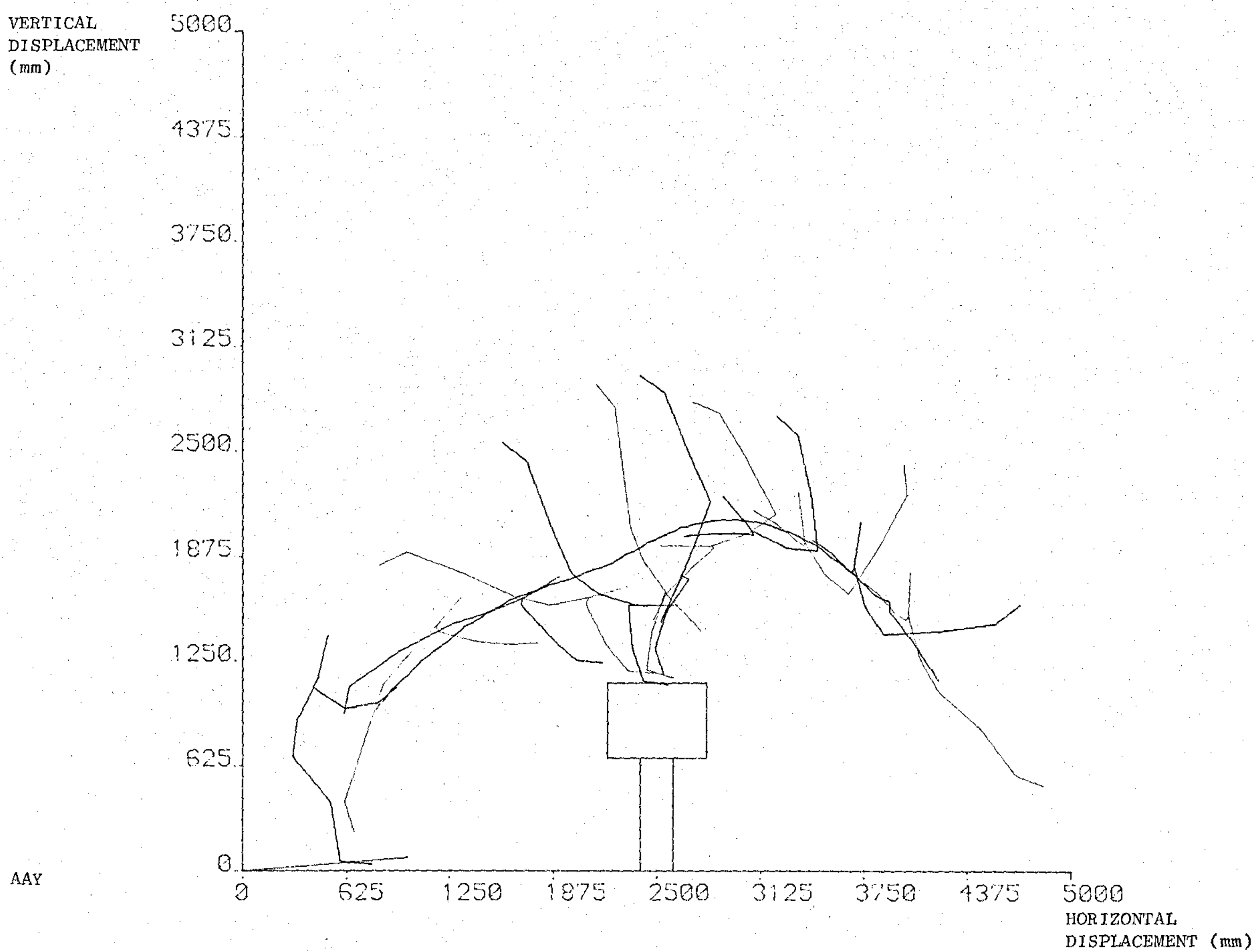
DISPLACEMENT (mm)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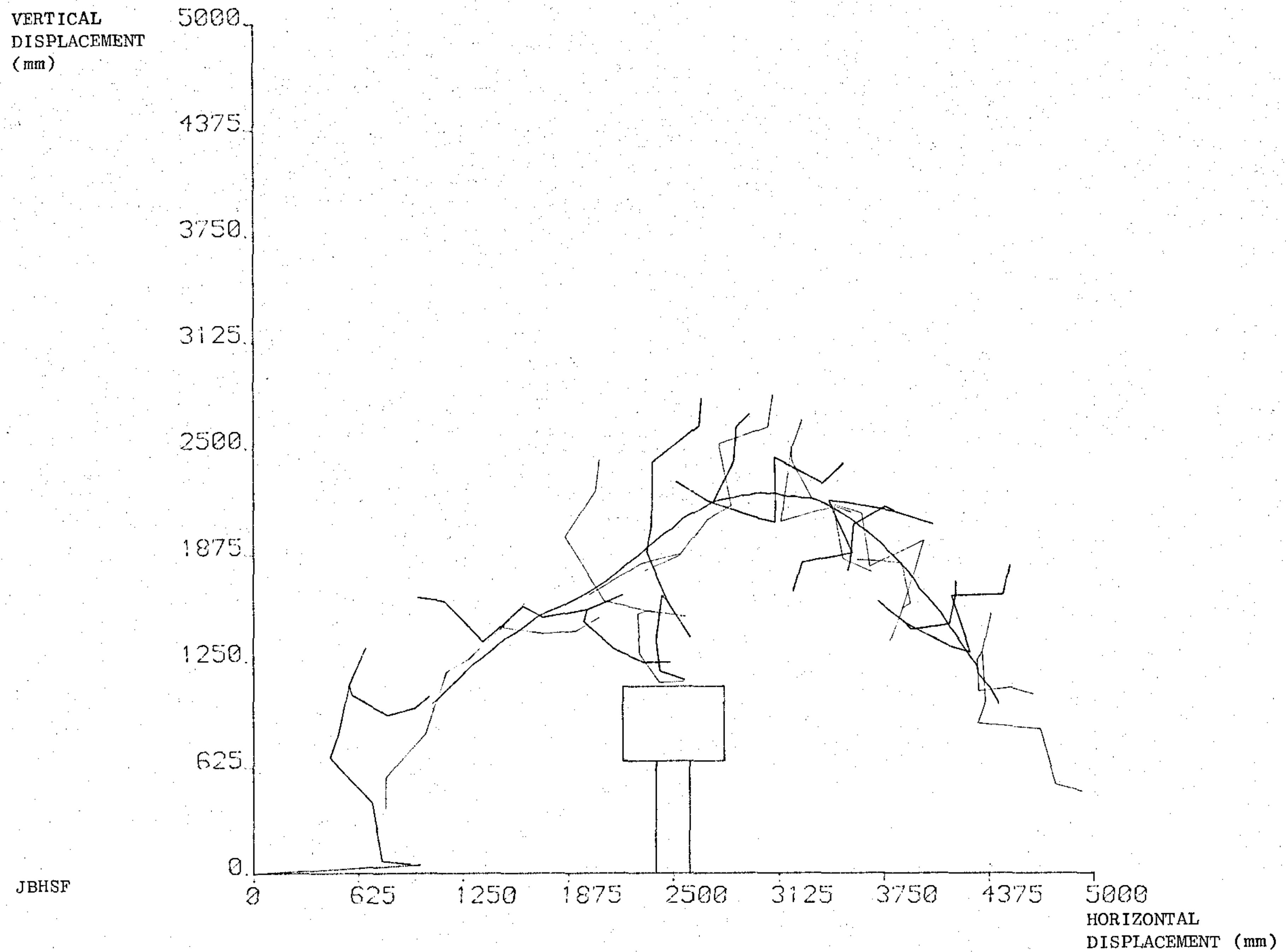
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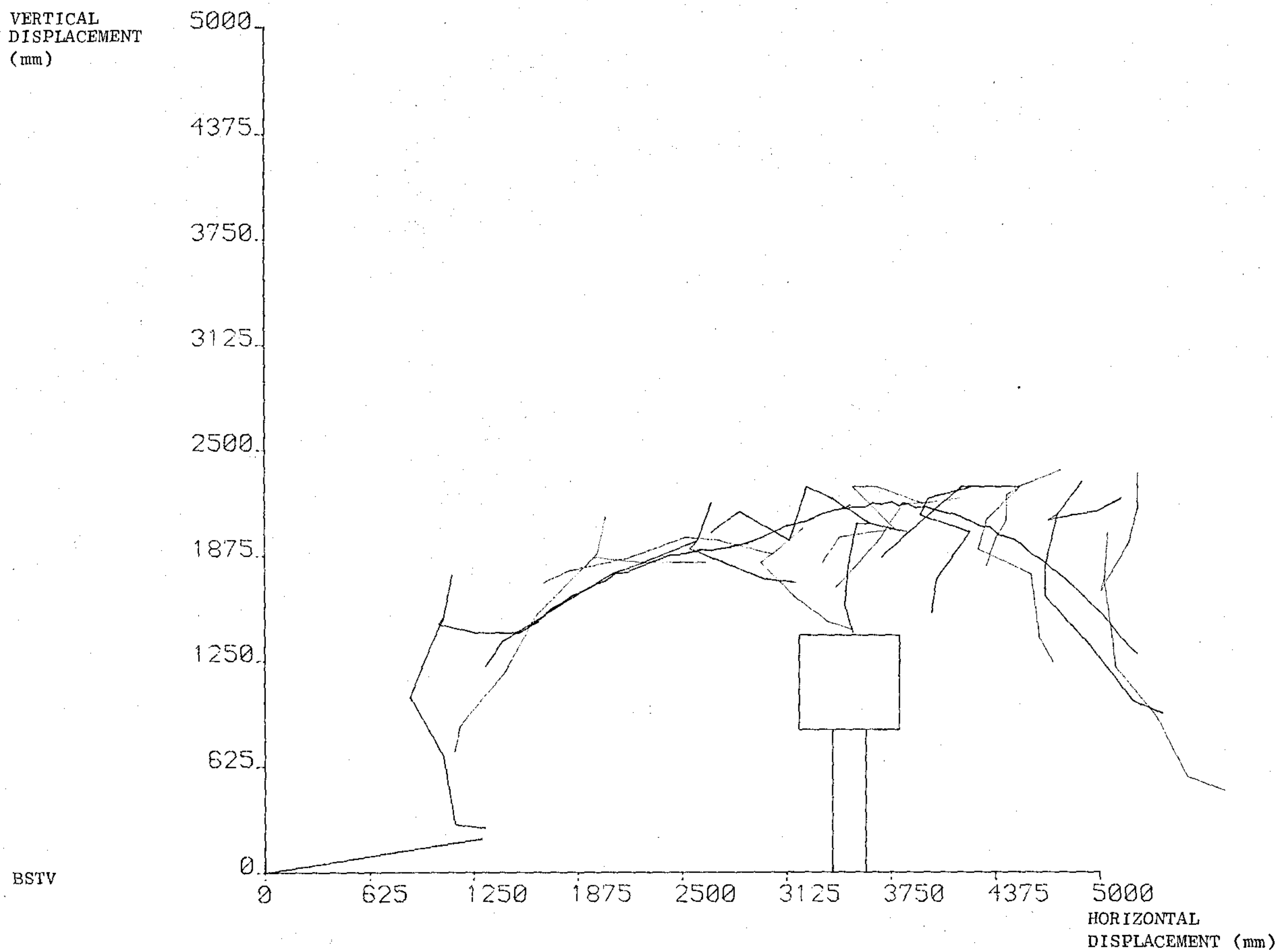

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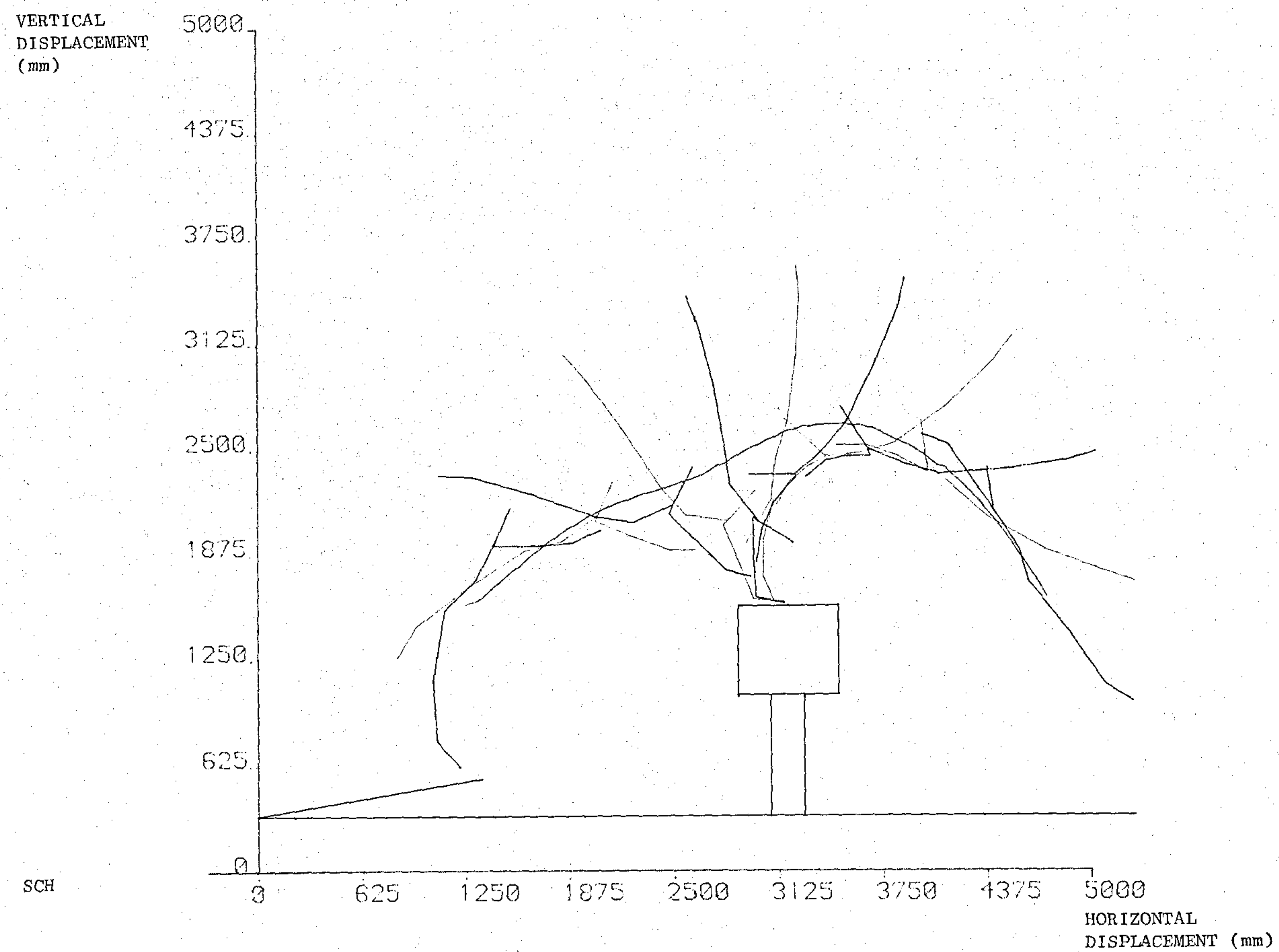
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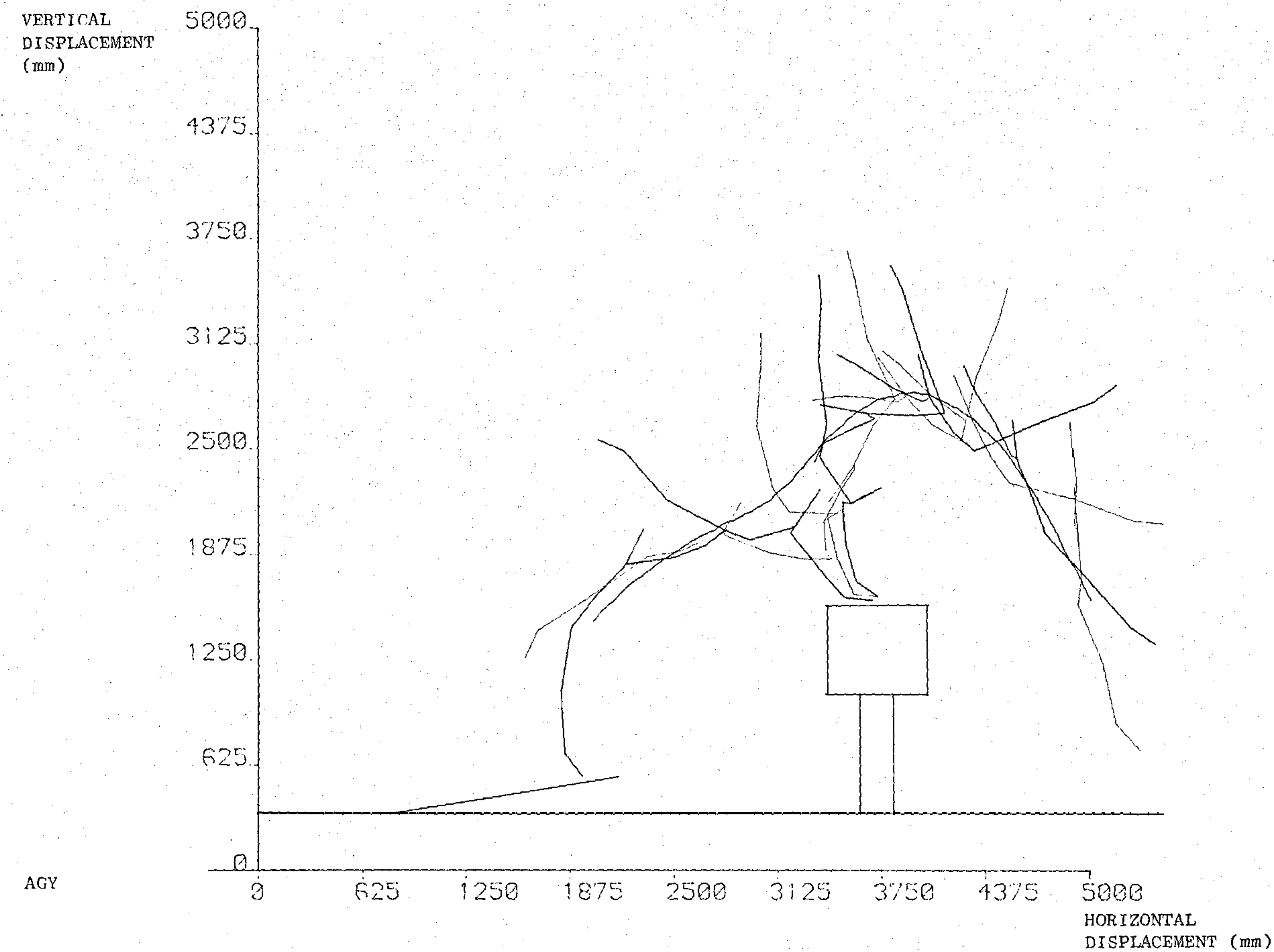
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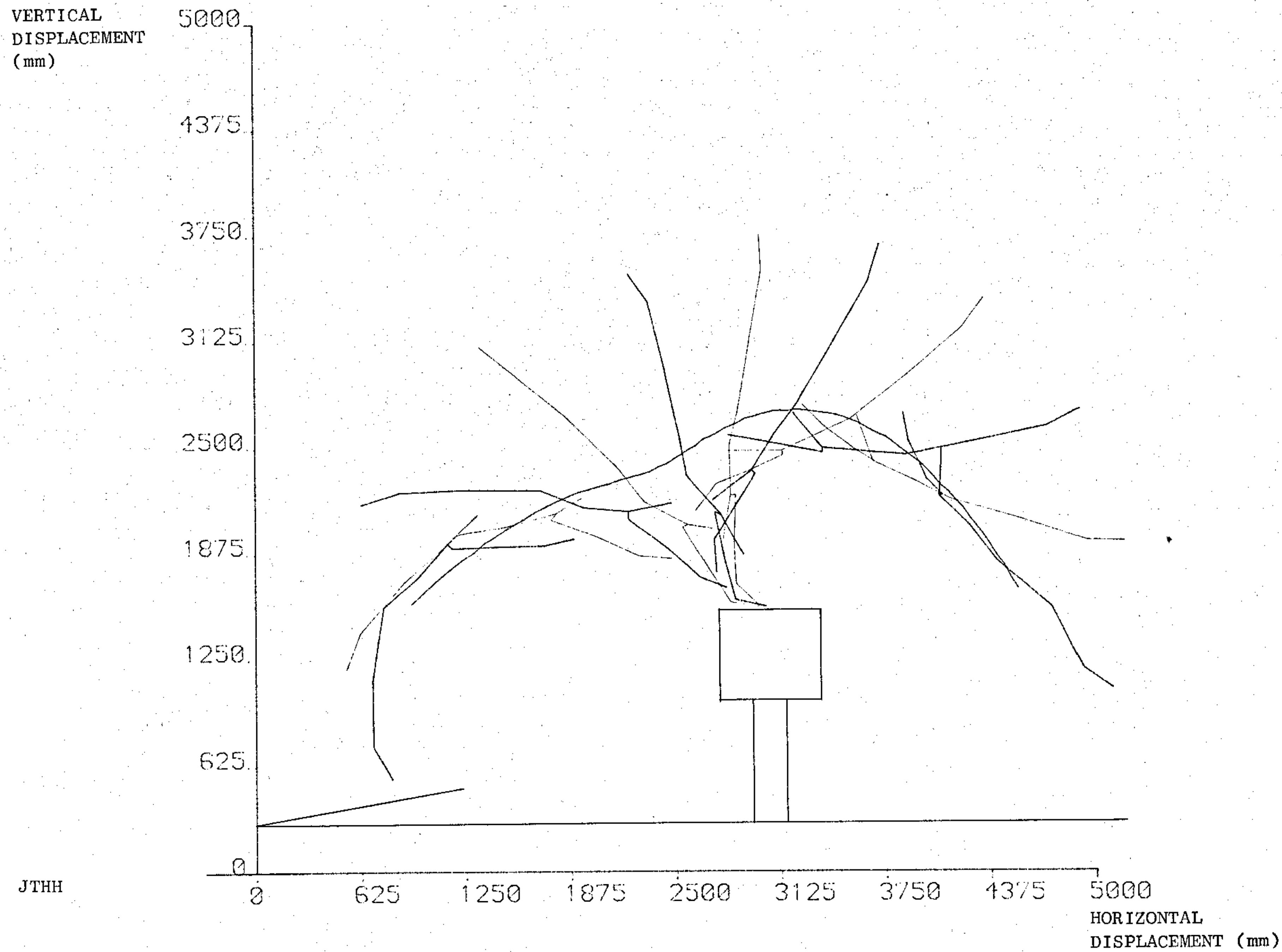
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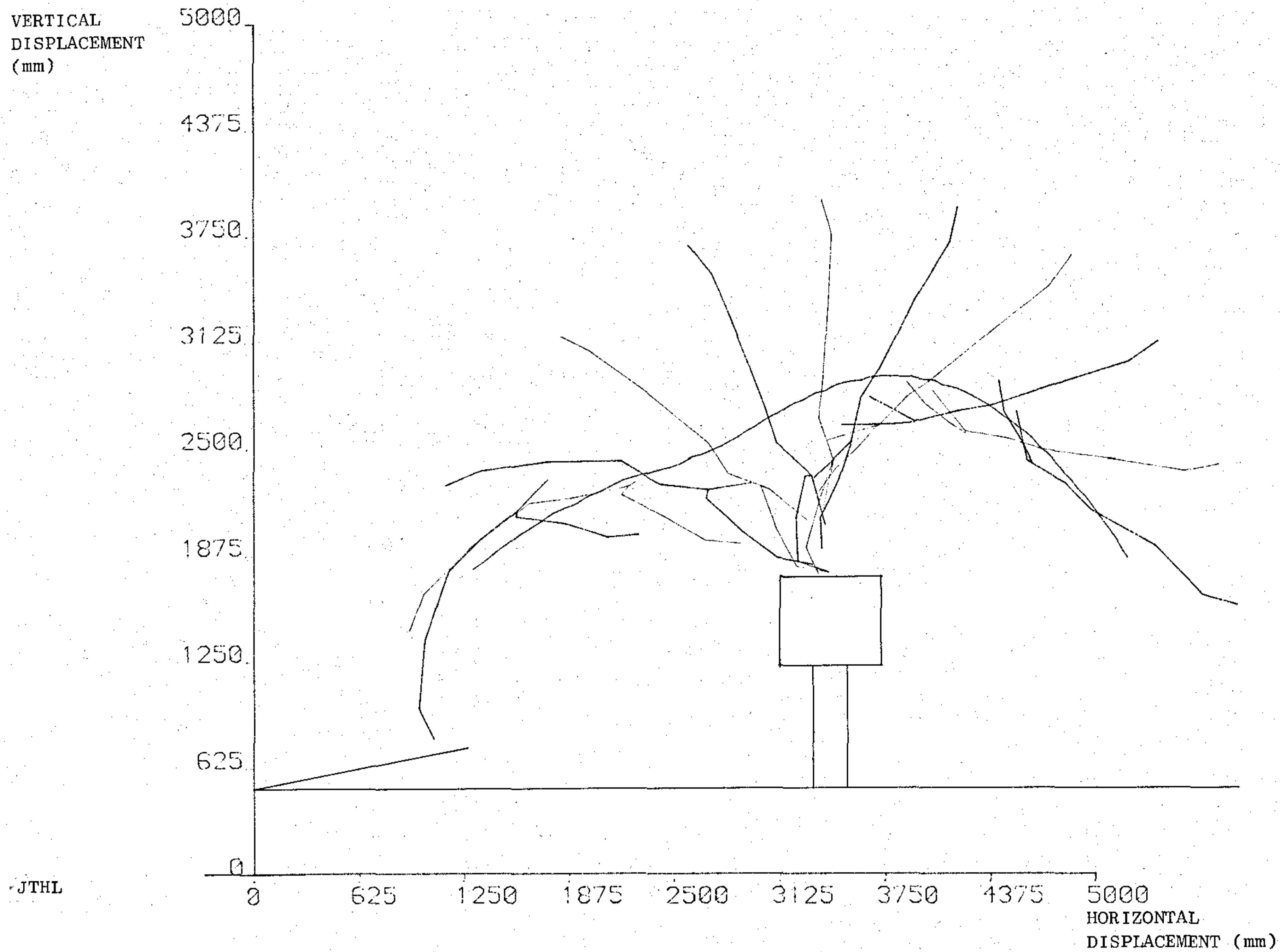
DISPLACEMENT (mm)
JTHH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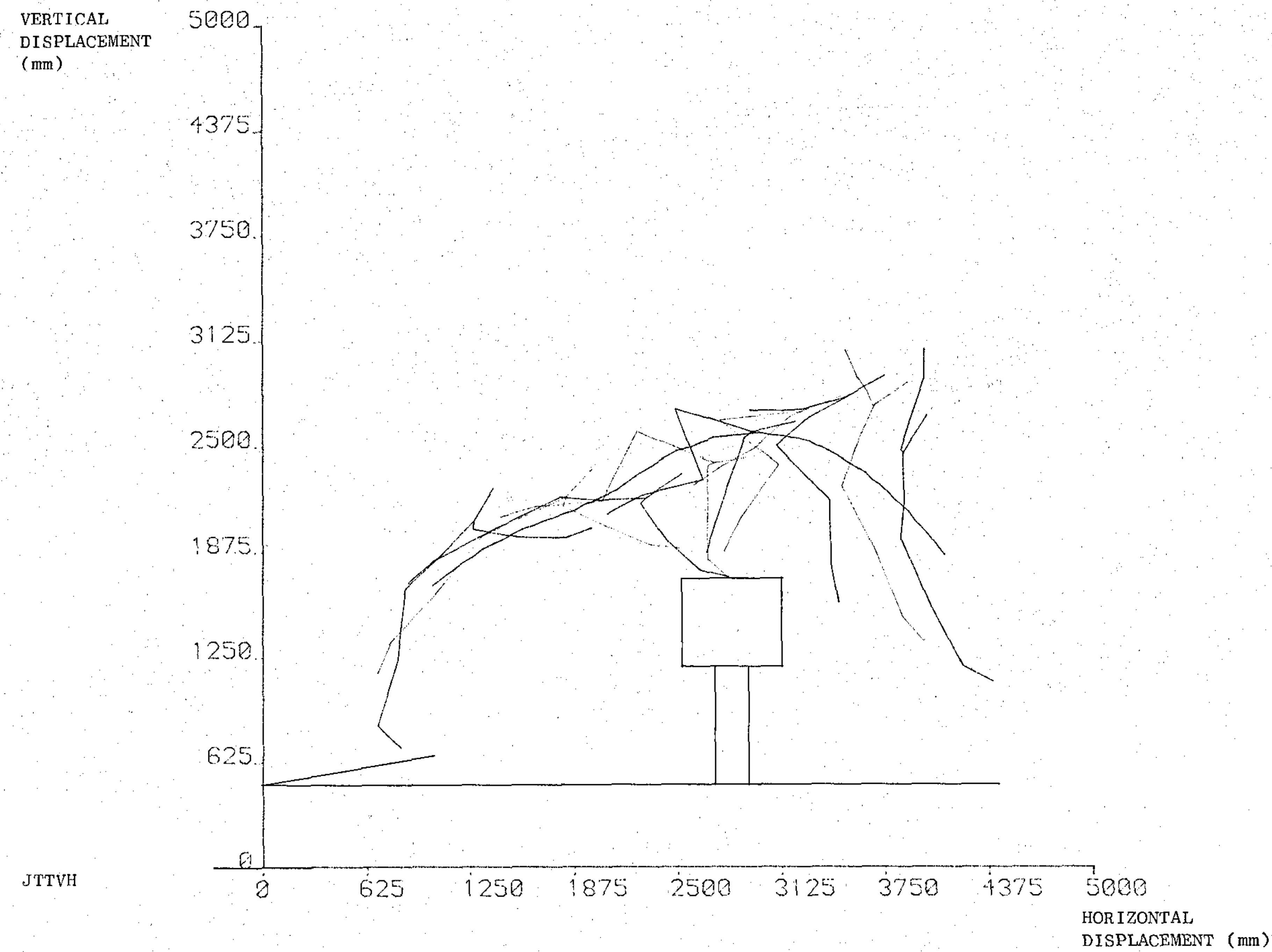
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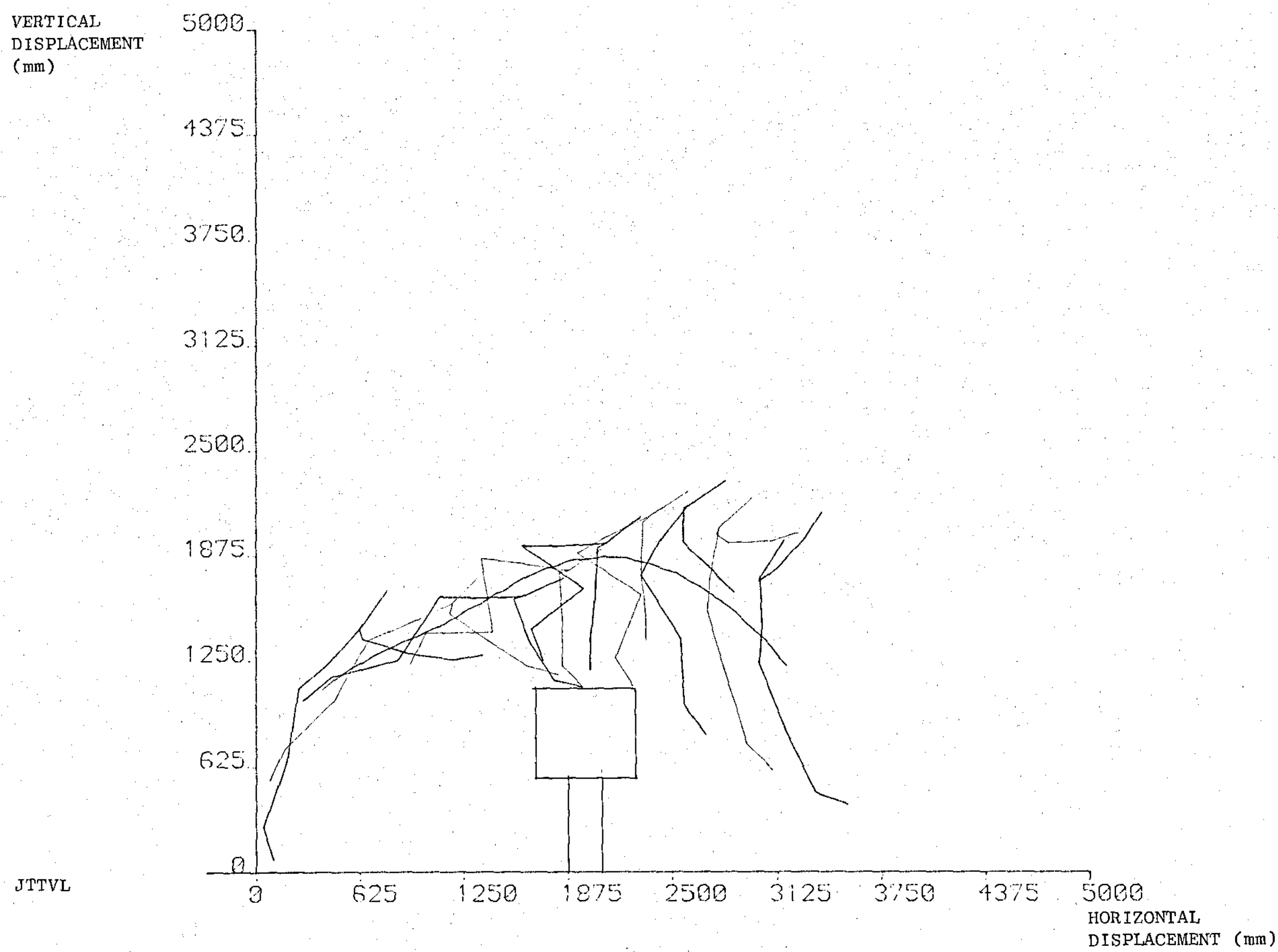
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2500
3125
3750
4375
5000
HORIZONTAL
DISPLACEMENT (mm)
JTTVL

APPENDIX B

Centre of gravity displacement and time data.

Note: The data for each of the 25 vaults in both experiments are presented. One vault per subject on each page.

HPTV

Preflight

x (m)	z (m)	t (s)
0.936	1.171	0.193
0.997	1.222	0.209
1.059	1.265	0.224
1.126	1.313	0.240
1.186	1.356	0.255
1.251	1.397	0.271
1.309	1.430	0.286
1.368	1.470	0.302
1.431	1.506	0.318
1.484	1.535	0.333
1.548	1.564	0.349
1.611	1.594	0.365
1.669	1.622	0.381
1.733	1.638	0.396
1.799	1.660	0.412
1.859	1.681	0.427
1.922	1.699	0.443

Contact

x (m)	z (m)	t (s)
1.987	1.706	0.459
2.058	1.704	0.475
2.106	1.720	0.491
2.162	1.734	0.506
2.206	1.745	0.522
2.252	1.760	0.538
2.295	1.784	0.554
2.340	1.801	0.569
2.382	1.817	0.585
2.422	1.839	0.601
2.461	1.857	0.617
2.510	1.874	0.632
2.554	1.888	0.648
2.594	1.897	0.664
2.636	1.910	0.680
2.680	1.919	0.696
2.719	1.927	0.711

Postflight

x (m)	z (m)	t (s)
2.763	1.937	0.727
2.811	1.937	0.743
2.852	1.935	0.759
2.895	1.933	0.774
2.941	1.929	0.790
2.979	1.922	0.806
3.021	1.914	0.822
3.065	1.895	0.837
3.104	1.883	0.853
3.147	1.872	0.869
3.193	1.849	0.885
3.245	1.822	0.901
3.281	1.805	0.916
3.324	1.777	0.932
3.365	1.746	0.948
3.408	1.710	0.964
3.461	1.680	0.979
3.498	1.645	0.995
3.548	1.610	1.010
3.591	1.566	1.027
3.632	1.526	1.042
3.679	1.479	1.058
3.719	1.434	1.074
3.761	1.391	1.090
3.810	1.323	1.106
3.851	1.269	1.121

JTTV

Preflight

x (m)	z (m)	t (s)
1.258	1.323	0.366
1.327	1.365	0.381
1.391	1.411	0.397
1.460	1.450	0.413
1.515	1.487	0.428
1.574	1.527	0.444
1.638	1.554	0.459
1.700	1.585	0.476
1.769	1.613	0.491
1.832	1.636	0.507
1.899	1.652	0.523
1.962	1.671	0.538
2.019	1.692	0.554

Contact

x (m)	z (m)	t (s)
2.080	1.711	0.570
2.134	1.730	0.586
2.191	1.757	0.601
2.243	1.791	0.617
2.290	1.819	0.633
2.341	1.847	0.648
2.384	1.881	0.664
2.433	1.908	0.680
2.487	1.936	0.695
2.536	1.972	0.711
2.589	1.996	0.727
2.638	2.021	0.743

Postflight

x (m)	z (m)	t (s)
2.689	2.041	0.758
2.739	2.055	0.774
2.790	2.070	0.790
2.836	2.084	0.805
2.884	2.096	0.821
2.930	2.100	0.837
2.982	2.101	0.852
3.026	2.107	0.868
3.071	2.107	0.884
3.120	2.099	0.900
3.169	2.092	0.915
3.218	2.080	0.931
3.267	2.064	0.947
3.318	2.044	0.962
3.368	2.037	0.978
3.421	2.013	0.994
3.472	1.984	1.010
3.528	1.967	1.025
3.570	1.936	1.041
3.614	1.905	1.057
3.662	1.867	1.072
3.710	1.825	1.088
3.754	1.779	1.104
3.804	1.743	1.119
3.852	1.690	1.135
3.905	1.647	1.151
3.950	1.604	1.167
3.994	1.545	1.182
4.045	1.496	1.198
4.095	1.434	1.214
4.140	1.372	1.230

JBTV

Preflight

x (m)	z (m)	t (s)
1.058	1.197	0.289
1.115	1.248	0.305
1.170	1.302	0.320
1.222	1.346	0.336
1.285	1.393	0.352
1.339	1.439	0.367
1.395	1.478	0.383
1.456	1.517	0.398
1.512	1.556	0.414
1.572	1.595	0.429
1.629	1.625	0.445
1.683	1.654	0.460
1.744	1.684	0.476
1.804	1.710	0.491
1.863	1.725	0.507
1.914	1.747	0.522

Contact

x (m)	z (m)	t (s)
1.981	1.765	0.538
2.035	1.783	0.553
2.091	1.800	0.569
2.145	1.826	0.584
2.195	1.846	0.599
2.243	1.872	0.615
2.286	1.904	0.630
2.336	1.927	0.646
2.386	1.949	0.661
2.435	1.971	0.676
2.487	1.992	0.691
2.541	2.016	0.707

Postflight

x (m)	z (m)	t (s)
2.592	2.033	0.722
2.641	2.047	0.738
2.699	2.063	0.753
2.741	2.068	0.768
2.796	2.076	0.784
2.842	2.080	0.799
2.889	2.092	0.815
2.945	2.082	0.829
2.996	2.075	0.845
3.048	2.072	0.861
3.096	2.061	0.876
3.148	2.054	0.891
3.198	2.026	0.907
3.247	2.021	0.922
3.297	2.005	0.937
3.343	1.985	0.953
3.391	1.967	0.968
3.450	1.949	0.983
3.496	1.926	0.999
3.552	1.895	1.014
3.600	1.867	1.030
3.653	1.830	1.045
3.703	1.793	1.060
3.758	1.749	1.076
3.802	1.710	1.091
3.851	1.665	1.106
3.897	1.625	1.122
3.949	1.577	1.137
3.994	1.529	1.153
4.042	1.471	1.169
4.097	1.420	1.183
4.146	1.360	1.199
4.199	1.297	1.214
4.244	1.228	1.229

TSTV

Preflight

x (m)	z (m)	t (s)
0.963	1.211	0.753
1.021	1.266	0.768
1.072	1.312	0.783
1.132	1.363	0.797
1.174	1.414	0.812
1.228	1.452	0.827
1.278	1.486	0.842
1.323	1.526	0.857
1.385	1.561	0.872
1.436	1.594	0.886
1.491	1.625	0.901
1.546	1.656	0.916
1.596	1.686	0.931
1.643	1.712	0.946
1.702	1.729	0.961
1.752	1.748	0.976
1.807	1.764	0.990
1.861	1.774	1.005
1.911	1.787	1.020

Contact

x (m)	z (m)	t (s)
1.973	1.791	1.035
2.020	1.799	1.050
2.072	1.811	1.065
2.119	1.822	1.080
2.162	1.835	1.095
2.213	1.848	1.110
2.250	1.859	1.125
2.300	1.872	1.140
2.343	1.886	1.155
2.380	1.897	1.170
2.421	1.915	1.185
2.460	1.926	1.200
2.515	1.933	1.215
2.556	1.945	1.230
2.610	1.952	1.245
2.656	1.957	1.260
2.698	1.965	1.275
2.737	1.968	1.290

Postflight

x (m)	z (m)	t (s)
2.790	1.971	1.305
2.833	1.973	1.320
2.881	1.965	1.335
2.932	1.962	1.350
2.971	1.955	1.365
3.017	1.942	1.380
3.059	1.922	1.395
3.107	1.915	1.410
3.153	1.897	1.425
3.198	1.875	1.440
3.245	1.854	1.455
3.288	1.826	1.470
3.340	1.801	1.485
3.382	1.772	1.500
3.429	1.739	1.515
3.475	1.709	1.530
3.517	1.669	1.545
3.568	1.634	1.560
3.606	1.590	1.575
3.650	1.548	1.590
3.699	1.506	1.605
3.748	1.461	1.620
3.790	1.403	1.635
3.835	1.350	1.650
3.879	1.294	1.665
3.925	1.234	1.680

AATV

Preflight			Postflight		
x (m)	z (m)	t (s)	x (m)	z (m)	t (s)
1.026	1.247	0.907	2.609	2.021	1.348
1.089	1.302	0.924	2.662	2.034	1.365
1.152	1.358	0.941	2.717	2.045	1.382
1.216	1.401	0.958	2.773	2.045	1.399
1.276	1.446	0.974	2.829	2.052	1.416
1.338	1.489	0.991	2.883	2.052	1.434
1.403	1.532	1.008	2.937	2.045	1.451
1.467	1.570	1.025	2.997	2.045	1.468
1.537	1.617	1.041	3.051	2.036	1.485
1.599	1.652	1.058	3.114	2.022	1.502
1.663	1.683	1.075	3.164	2.003	1.519
1.730	1.715	1.092	3.219	1.982	1.537
1.797	1.738	1.109	3.271	1.962	1.554
1.861	1.759	1.125	3.345	1.944	1.571
			3.399	1.922	1.588
			3.455	1.902	1.605
Contact			3.518	1.870	1.622
			3.576	1.829	1.639
1.932	1.780	1.142	3.631	1.804	1.657
1.991	1.799	1.159	3.690	1.763	1.674
2.057	1.820	1.176	3.741	1.720	1.691
2.117	1.845	1.193	3.794	1.673	1.708
2.172	1.866	1.211	3.857	1.630	1.725
2.225	1.886	1.228	3.910	1.574	1.742
2.281	1.909	1.245	3.970	1.516	1.759
2.333	1.936	1.262	4.020	1.457	1.777
2.387	1.954	1.279	4.078	1.403	1.794
2.440	1.975	1.296	4.139	1.333	1.811
2.498	1.995	1.313			
2.553	2.011	1.331			

DMTV

Preflight

x (m)	z (m)	t (s)
1.042	1.260	1.065
1.102	1.315	1.081
1.164	1.364	1.097
1.224	1.404	1.112
1.283	1.446	1.128
1.347	1.488	1.144
1.409	1.530	1.159
1.473	1.567	1.175
1.533	1.597	1.190
1.595	1.627	1.206
1.659	1.660	1.222
1.720	1.686	1.237
1.785	1.704	1.253
1.850	1.727	1.269
1.917	1.744	1.284

Contact

x (m)	z (m)	t (s)
1.980	1.759	1.300
2.038	1.764	1.316
2.099	1.780	1.332
2.157	1.799	1.347
2.207	1.810	1.363
2.262	1.827	1.379
2.314	1.854	1.394
2.362	1.875	1.401
2.401	1.897	1.416
2.452	1.913	1.441
2.504	1.933	1.457
2.563	1.957	1.473
2.620	1.972	1.488

Postflight

x (m)	z (m)	t (s)
2.673	1.984	1.504
2.732	1.991	1.520
2.785	2.003	1.535
2.842	2.012	1.551
2.896	2.019	1.567
2.949	2.016	1.582
3.001	2.020	1.598
3.049	2.019	1.613
3.106	2.008	1.629
3.165	1.995	1.645
3.220	1.990	1.660
3.274	1.980	1.676
3.331	1.962	1.692
3.387	1.939	1.707
3.434	1.895	1.723
3.483	1.875	1.739
3.538	1.850	1.754
3.589	1.815	1.770
3.645	1.794	1.786
3.700	1.757	1.801
3.754	1.722	1.817
3.801	1.685	1.833
3.856	1.648	1.848
3.912	1.609	1.864
3.965	1.564	1.880
4.015	1.510	1.895
4.072	1.460	1.911
4.125	1.419	1.927
4.171	1.362	1.942
4.225	1.299	1.958

HPH

Preflight

x (m)	z (m)	t (s)
0.641	1.088	0.233
0.697	1.149	0.249
0.753	1.211	0.264
0.807	1.268	0.280
0.862	1.316	0.295
0.912	1.368	0.310
0.977	1.414	0.326
1.027	1.459	0.341
1.085	1.506	0.357
1.136	1.547	0.372
1.193	1.582	0.388
1.243	1.621	0.403
1.302	1.653	0.418
1.356	1.682	0.434
1.408	1.718	0.449
1.470	1.735	0.465
1.526	1.759	0.480
1.581	1.783	0.496
1.632	1.799	0.511
1.685	1.813	0.526
1.737	1.828	0.541
1.791	1.840	0.557
1.848	1.849	0.573
1.904	1.855	0.588

Contact

x (m)	z (m)	t (s)
1.956	1.853	0.604
2.012	1.860	0.618
2.069	1.860	0.635
2.118	1.867	0.650
2.165	1.872	0.666
2.213	1.875	0.681
2.249	1.888	0.697
2.289	1.905	0.712
2.323	1.911	0.726
2.359	1.920	0.743
2.398	1.943	0.759
2.433	1.951	0.774
2.464	1.962	0.790
2.502	1.978	0.805
2.534	1.990	0.821
2.562	2.006	0.837
2.594	2.015	0.852
2.624	2.023	0.868
2.655	2.030	0.883
2.687	2.041	0.899
2.717	2.045	0.914
2.749	2.052	0.930
2.775	2.061	0.945
2.804	2.069	0.961
2.833	2.074	0.976
2.866	2.077	0.992
2.896	2.076	1.007
2.923	2.071	1.023

Postflight

x (m)	z (m)	t (s)
2.953	2.072	1.038
2.980	2.064	1.054
3.007	2.064	1.069
3.040	2.049	1.085
3.063	2.030	1.100
3.090	2.016	1.116
3.120	1.994	1.132
3.147	1.973	1.147
3.178	1.954	1.163
3.207	1.928	1.178
3.233	1.901	1.194
3.266	1.871	1.209
3.288	1.836	1.225
3.323	1.800	1.240
3.343	1.764	1.256
3.374	1.720	1.271
3.399	1.677	1.287
3.429	1.629	1.302
3.453	1.583	1.318
3.481	1.528	1.333
3.505	1.473	1.349
3.531	1.418	1.364
3.559	1.360	1.380
3.587	1.296	1.395
3.616	1.235	1.411

JTH

Preflight

x (m)	z (m)	t (s)
1.016	1.332	0.895
1.071	1.391	0.910
1.130	1.452	0.925
1.182	1.502	0.941
1.241	1.550	0.958
1.299	1.603	0.974
1.351	1.651	0.989
1.407	1.688	1.005
1.463	1.730	1.022
1.516	1.773	1.038
1.573	1.816	1.055
1.635	1.846	1.070
1.683	1.878	1.085
1.738	1.914	1.101
1.792	1.939	1.118
1.847	1.967	1.135
1.898	1.991	1.150
1.956	2.007	1.166
2.012	2.030	1.183
2.070	2.044	1.200

Contact

x (m)	z (m)	t (s)
2.119	2.054	1.215
2.170	2.069	1.230
2.224	2.080	1.245
2.277	2.092	1.262
2.325	2.104	1.280
2.370	2.123	1.297
2.412	2.139	1.312
2.453	2.169	1.327
2.491	2.188	1.343
2.531	2.212	1.360
2.569	2.234	1.375
2.602	2.253	1.390
2.640	2.272	1.404
2.672	2.297	1.421
2.705	2.311	1.440
2.737	2.319	1.455
2.775	2.351	1.470
2.806	2.366	1.485

Postflight

x (m)	z (m)	t (s)
2.843	2.378	1.501
2.876	2.381	1.518
2.906	2.396	1.535
2.943	2.403	1.550
2.980	2.401	1.565
3.016	2.393	1.580
3.050	2.394	1.597
3.086	2.394	1.615
3.124	2.382	1.630
3.157	2.367	1.647
3.194	2.363	1.663
3.231	2.343	1.680
3.275	2.327	1.695
3.312	2.295	1.713
3.351	2.273	1.729
3.387	2.250	1.744
3.423	2.212	1.762
3.457	2.180	1.779
3.495	2.150	1.795
3.527	2.111	1.812
3.567	2.065	1.827
3.610	2.026	1.841
3.647	1.976	1.859
3.679	1.927	1.877
3.715	1.873	1.892
3.751	1.819	1.907
3.789	1.763	1.923
3.828	1.702	1.942
3.860	1.636	1.958
3.897	1.576	1.975
3.933	1.505	1.990
3.975	1.436	2.005

JBH

Preflight

x (m)	z (m)	t (s)
1.189	1.303	0.143
1.238	1.360	0.158
1.292	1.412	0.173
1.351	1.467	0.188
1.410	1.520	0.203
1.467	1.562	0.218
1.525	1.611	0.233
1.587	1.662	0.248
1.646	1.698	0.263
1.704	1.730	0.278
1.768	1.765	0.294
1.821	1.800	0.309
1.885	1.831	0.324
1.946	1.861	0.339
2.006	1.878	0.354

Contact

x (m)	z (m)	t (s)
2.068	1.901	0.369
2.123	1.927	0.383
2.175	1.953	0.399
2.222	1.972	0.414
2.269	1.999	0.429
2.311	2.032	0.444
2.352	2.057	0.459
2.399	2.087	0.474
2.444	2.115	0.489
2.480	2.149	0.504
2.520	2.164	0.519
2.553	2.193	0.534
2.591	2.224	0.549
2.629	2.249	0.564
2.661	2.266	0.579

Postflight

x (m)	z (m)	t (s)
2.700	2.281	0.594
2.736	2.297	0.609
2.774	2.323	0.624
2.811	2.337	0.639
2.848	2.346	0.654
2.888	2.352	0.669
2.929	2.366	0.684
2.965	2.365	0.699
3.001	2.372	0.714
3.038	2.367	0.729
3.081	2.365	0.744
3.118	2.361	0.759
3.158	2.350	0.774
3.197	2.336	0.789
3.234	2.327	0.804
3.273	2.308	0.819
3.310	2.289	0.834
3.358	2.268	0.849
3.392	2.240	0.864
3.425	2.213	0.879
3.462	2.185	0.895
3.505	2.150	0.910
3.544	2.118	0.925
3.584	2.081	0.940
3.623	2.040	0.955
3.660	1.999	0.970
3.695	1.951	0.985
3.731	1.908	1.000
3.771	1.859	1.015
3.801	1.808	1.030
3.839	1.750	1.045
3.871	1.697	1.060
3.904	1.633	1.075
3.941	1.581	1.090
3.975	1.520	1.105
4.013	1.449	1.120
4.050	1.386	1.135
4.086	1.317	1.150
4.125	1.237	1.165
4.155	1.172	1.180

TSH

Preflight

x (m)	z (m)	t (s)
1.099	1.255	0.797
1.162	1.318	0.812
1.212	1.370	0.827
1.264	1.420	0.842
1.319	1.468	0.857
1.379	1.516	0.873
1.429	1.568	0.888
1.484	1.606	0.903
1.535	1.646	0.918
1.591	1.686	0.933
1.648	1.718	0.949
1.702	1.751	0.964
1.757	1.794	0.979
1.812	1.813	0.994
1.866	1.840	1.009
1.927	1.871	1.025
1.988	1.888	1.040

Contact

x (m)	z (m)	t (s)
2.042	1.907	1.055
2.092	1.928	1.070
2.150	1.939	1.085
2.200	1.954	1.100
2.252	1.971	1.116
2.299	1.986	1.131
2.345	2.006	1.146
2.383	2.018	1.161
2.428	2.034	1.176
2.472	2.057	1.191
2.510	2.077	1.206
2.554	2.091	1.221
2.592	2.107	1.237
2.635	2.118	1.252
2.674	2.139	1.267
2.713	2.157	1.282
2.753	2.166	1.297
2.791	2.182	1.312
2.828	2.192	1.327
2.865	2.199	1.342
2.906	2.205	1.357
2.948	2.216	1.373
2.984	2.229	1.388
3.021	2.242	1.403
3.047	2.241	1.418
3.081	2.250	1.433
3.119	2.263	1.448
3.158	2.258	1.463

Postflight

x (m)	z (m)	t (s)
3.197	2.257	1.479
3.233	2.263	1.494
3.270	2.260	1.509
3.315	2.256	1.524
3.353	2.251	1.539
3.387	2.236	1.554
3.431	2.229	1.569
3.467	2.221	1.584
3.510	2.199	1.600
3.548	2.182	1.615
3.589	2.163	1.630
3.631	2.136	1.645
3.667	2.106	1.660
3.704	2.082	1.675
3.746	2.051	1.690
3.781	2.019	1.703
3.824	1.979	1.721
3.861	1.937	1.736
3.905	1.900	1.751
3.938	1.857	1.766
3.978	1.805	1.781
4.021	1.756	1.796
4.054	1.701	1.811
4.087	1.655	1.826
4.134	1.599	1.842
4.171	1.539	1.857
4.205	1.477	1.872
4.243	1.427	1.887

AAH

Preflight

x (m)	z (m)	t (s)
0.949	1.231	0.231
1.007	1.295	0.247
1.067	1.359	0.263
1.126	1.418	0.279
1.188	1.476	0.295
1.246	1.525	0.311
1.309	1.579	0.327
1.370	1.622	0.344
1.433	1.669	0.360
1.490	1.710	0.376
1.545	1.758	0.392
1.608	1.790	0.408
1.665	1.829	0.424
1.727	1.864	0.441
1.785	1.890	0.457
1.845	1.916	0.473
1.908	1.948	0.489
1.966	1.967	0.505
2.023	1.985	0.521
2.080	2.001	0.537
2.143	2.016	0.554

Contact

x (m)	z (m)	t (s)
2.203	2.028	0.570
2.267	2.039	0.586
2.323	2.054	0.602
2.374	2.063	0.618
2.427	2.077	0.634
2.479	2.096	0.650
2.530	2.120	0.666
2.577	2.136	0.683
2.621	2.157	0.700
2.665	2.177	0.715
2.706	2.198	0.731
2.751	2.211	0.747
2.793	2.236	0.763
2.842	2.238	0.780
2.882	2.250	0.796
2.924	2.265	0.812

Postflight

x (m)	z (m)	t (s)
2.968	2.276	0.828
3.010	2.282	0.844
3.049	2.293	0.861
3.093	2.291	0.877
3.142	2.284	0.894
3.181	2.273	0.910
3.224	2.272	0.926
3.273	2.263	0.943
3.315	2.246	0.959
3.354	2.234	0.976
3.402	2.216	0.992
3.445	2.193	1.008
3.487	2.168	1.025
3.536	2.144	1.041
3.580	2.113	1.058
3.621	2.076	1.074
3.660	2.050	1.090
3.702	1.999	1.107
3.745	1.962	1.123
3.788	1.921	1.140
3.830	1.876	1.156
3.875	1.817	1.172
3.912	1.772	1.189
3.955	1.717	1.205
3.999	1.658	1.222
4.038	1.600	1.238
4.081	1.540	1.254
4.126	1.483	1.271
4.169	1.406	1.287
4.212	1.327	1.304

DMH

Preflight

x (m)	z (m)	t (s)
1.113	1.276	0.592
1.175	1.344	0.607
1.228	1.397	0.623
1.279	1.458	0.637
1.340	1.507	0.653
1.400	1.549	0.669
1.453	1.600	0.684
1.508	1.647	0.700
1.564	1.693	0.715
1.624	1.731	0.731
1.676	1.771	0.746
1.731	1.810	0.762
1.789	1.838	0.777
1.851	1.863	0.793
1.906	1.898	0.808
1.965	1.928	0.824
2.024	1.954	0.839
2.078	1.969	0.855
2.143	1.990	0.870

Contact

x (m)	z (m)	t (s)
2.196	2.007	0.886
2.254	2.020	0.901
2.313	2.034	0.917
2.367	2.043	0.932
2.419	2.066	0.948
2.472	2.090	0.963
2.513	2.096	0.979
2.564	2.118	0.994
2.608	2.136	1.010
2.646	2.157	1.025
2.692	2.179	1.041
2.732	2.198	1.056
2.771	2.216	1.072
2.812	2.240	1.087
2.847	2.252	1.103
2.889	2.270	1.118
2.924	2.286	1.133
2.966	2.298	1.149
3.004	2.308	1.164

Postflight

x (m)	z (m)	t (s)
3.042	2.315	1.180
3.083	2.320	1.195
3.127	2.327	1.211
3.180	2.349	1.226
3.206	2.328	1.242
3.248	2.324	1.257
3.287	2.313	1.273
3.325	2.300	1.288
3.364	2.293	1.304
3.406	2.279	1.319
3.440	2.261	1.335
3.488	2.241	1.350
3.530	2.218	1.366
3.573	2.187	1.381
3.611	2.163	1.397
3.649	2.131	1.412
3.693	2.096	1.428
3.730	2.061	1.443
3.772	2.023	1.459
3.805	1.983	1.474
3.851	1.940	1.490
3.890	1.892	1.505
3.927	1.836	1.521
3.964	1.794	1.536
4.004	1.730	1.552
4.042	1.676	1.567
4.081	1.621	1.583
4.126	1.563	1.598
4.162	1.504	1.614
4.195	1.436	1.629
4.236	1.370	1.645

HPY

Preflight

x (m)	z (m)	t (s)
0.950	0.987	0.575
0.999	1.046	0.590
1.046	1.113	0.606
1.096	1.161	0.622
1.142	1.216	0.638
1.186	1.264	0.653
1.234	1.311	0.669
1.284	1.357	0.685
1.333	1.403	0.700
1.379	1.434	0.716
1.424	1.472	0.732
1.470	1.511	0.747
1.521	1.548	0.763
1.565	1.572	0.779
1.615	1.599	0.794
1.665	1.625	0.810
1.711	1.652	0.826
1.763	1.667	0.841
1.812	1.687	0.857
1.860	1.706	0.873
1.909	1.715	0.888

Contact

x (m)	z (m)	t (s)
1.955	1.731	0.904
2.007	1.747	0.920
2.052	1.753	0.936
2.092	1.774	0.951
2.135	1.789	0.967
2.176	1.811	0.983
2.207	1.836	0.998
2.242	1.865	1.014
2.288	1.886	1.030
2.322	1.914	1.045
2.364	1.934	1.061
2.395	1.958	1.077
2.434	1.977	1.092

Postflight

x (m)	z (m)	t (s)
2.463	1.989	1.108
2.496	2.007	1.124
2.530	2.025	1.139
2.561	2.034	1.155
2.598	2.046	1.171
2.629	2.051	1.186
2.665	2.056	1.202
2.695	2.057	1.218
2.734	2.058	1.234
2.780	2.047	1.249
2.805	2.046	1.265
2.848	2.037	1.281
2.880	2.026	1.296
2.917	2.009	1.312
2.956	1.994	1.328
2.987	1.968	1.343
3.019	1.951	1.359
3.061	1.925	1.375
3.095	1.897	1.390
3.131	1.866	1.406
3.160	1.841	1.422
3.199	1.810	1.437
3.232	1.779	1.453
3.268	1.739	1.469
3.300	1.697	1.484
3.335	1.653	1.500
3.369	1.609	1.516
3.400	1.565	1.531
3.435	1.516	1.547
3.479	1.459	1.563
3.509	1.403	1.579
3.543	1.349	1.594
3.580	1.285	1.610
3.620	1.220	1.626
3.653	1.158	1.641
3.689	1.084	1.657

JTY

Preflight

x (m)	z (m)	t (s)
0.751	1.191	0.925
0.813	1.247	0.941
0.875	1.305	0.957
0.939	1.358	0.973
1.001	1.403	0.989
1.061	1.456	1.005
1.130	1.501	1.021
1.186	1.548	1.038
1.253	1.582	1.054
1.313	1.631	1.070
1.384	1.664	1.086
1.442	1.692	1.102
1.506	1.724	1.118
1.567	1.757	1.134
1.622	1.777	1.150
1.689	1.799	1.166
1.754	1.819	1.183
1.817	1.825	1.199

Contact

x (m)	z (m)	t (s)
1.887	1.851	1.215
1.944	1.859	1.232
2.053	1.889	1.265
2.107	1.911	1.281
2.155	1.933	1.298
2.195	1.954	1.315
2.234	1.982	1.332
2.280	2.008	1.348
2.321	2.044	1.365
2.360	2.077	1.381
2.402	2.104	1.398
2.437	2.132	1.415
2.488	2.165	1.431

Postflight

x (m)	z (m)	t (s)
2.525	2.186	1.448
2.570	2.214	1.465
2.611	2.228	1.481
2.650	2.245	1.498
2.697	2.262	1.515
2.735	2.269	1.531
2.774	2.284	1.548
2.827	2.300	1.564
2.872	2.295	1.581
2.918	2.295	1.598
2.965	2.301	1.614
3.007	2.295	1.631
3.057	2.283	1.648
3.096	2.277	1.664
3.139	2.265	1.681
3.183	2.254	1.698
3.240	2.233	1.714
3.343	2.186	1.748
3.391	2.158	1.764
3.440	2.133	1.781
3.490	2.097	1.799
3.540	2.053	1.814
3.587	2.016	1.831
3.628	1.973	1.847
3.675	1.925	1.864
3.725	1.873	1.881
3.771	1.821	1.897
3.819	1.765	1.914
3.864	1.715	1.931
3.909	1.646	1.947
3.956	1.576	1.964
3.995	1.516	1.981
4.047	1.441	1.997
4.087	1.368	2.014
4.128	1.289	2.030

JBY

Preflight

x (m)	z (m)	t (s)
1.132	1.095	0.578
1.188	1.146	0.593
1.246	1.211	0.609
1.307	1.268	0.624
1.367	1.316	0.638
1.428	1.374	0.653
1.486	1.422	0.669
1.545	1.462	0.683
1.610	1.509	0.699
1.668	1.552	0.714
1.723	1.591	0.729
1.788	1.631	0.744
1.853	1.666	0.759
1.915	1.699	0.774
1.979	1.729	0.789
2.043	1.756	0.804
2.114	1.781	0.819
2.178	1.803	0.834
2.244	1.819	0.849

Contact

x (m)	z (m)	t (s)
2.307	1.831	0.864
2.368	1.849	0.879
2.428	1.861	0.894
2.484	1.878	0.910
2.531	1.906	0.924
2.582	1.924	0.940
2.622	1.943	0.955
2.666	1.969	0.970
2.711	1.989	0.985
2.746	2.015	1.000
2.785	2.041	1.015
2.819	2.062	1.030
2.854	2.091	1.045
2.895	2.111	1.060
2.929	2.135	1.076

Postflight

x (m)	z (m)	t (s)
2.965	2.160	1.091
2.998	2.181	1.106
3.035	2.200	1.121
3.072	2.215	1.136
3.115	2.224	1.151
3.157	2.233	1.166
3.205	2.250	1.181
3.247	2.257	1.196
3.287	2.265	1.211
3.335	2.262	1.226
3.381	2.263	1.241
3.427	2.261	1.256
3.467	2.257	1.271
3.518	2.245	1.286
3.561	2.236	1.302
3.605	2.227	1.317
3.653	2.213	1.332
3.703	2.193	1.347
3.749	2.177	1.361
3.800	2.150	1.377
3.841	2.124	1.392
3.890	2.089	1.407
3.942	2.058	1.422
3.978	2.024	1.437
4.030	1.987	1.452
4.065	1.949	1.467
4.111	1.911	1.482
4.153	1.867	1.497
4.200	1.821	1.512
4.236	1.772	1.527
4.277	1.715	1.542
4.318	1.665	1.558
4.366	1.614	1.573
4.404	1.550	1.588
4.444	1.491	1.603
4.485	1.429	1.618
4.524	1.362	1.633
4.564	1.298	1.648
4.610	1.230	1.663

TSY

Preflight

x (m)	z (m)	t (s)
1.097	1.056	1.015
1.150	1.147	1.030
1.209	1.200	1.045
1.266	1.243	1.060
1.320	1.285	1.075
1.374	1.337	1.090
1.426	1.372	1.105
1.481	1.409	1.120
1.533	1.442	1.135
1.591	1.475	1.150
1.644	1.518	1.165
1.694	1.551	1.180
1.753	1.575	1.195

Contact

x (m)	z (m)	t (s)
1.816	1.608	1.210
1.870	1.636	1.225
1.922	1.655	1.240
1.975	1.684	1.255
2.026	1.705	1.270
2.084	1.728	1.285
2.131	1.754	1.300
2.175	1.773	1.315
2.226	1.797	1.330
2.267	1.824	1.345
2.314	1.844	1.360
2.352	1.865	1.375
2.395	1.888	1.390
2.447	1.898	1.405
2.488	1.924	1.420
2.533	1.931	1.435
2.577	1.947	1.450
2.618	1.970	1.465
2.669	1.991	1.480
2.713	2.002	1.495

Postflight

x (m)	z (m)	t (s)
2.761	2.015	1.510
2.804	2.026	1.525
2.843	2.038	1.541
2.899	2.037	1.556
2.933	2.030	1.571
2.984	2.038	1.586
3.037	2.027	1.601
3.077	2.019	1.617
3.126	2.005	1.632
3.180	2.001	1.647
3.218	1.988	1.662
3.271	1.974	1.678
3.311	1.956	1.693
3.367	1.934	1.708
3.414	1.908	1.723
3.461	1.894	1.738
3.506	1.857	1.754
3.559	1.819	1.769
3.599	1.793	1.784
3.647	1.763	1.799
3.696	1.726	1.812
3.732	1.691	1.830
3.778	1.644	1.845
3.826	1.599	1.860
3.869	1.552	1.875
3.916	1.499	1.891
3.957	1.450	1.906
4.001	1.394	1.921
4.043	1.334	1.936
4.081	1.279	1.952
4.125	1.212	1.967

AAY

Preflight

x (m)	z (m)	t (s)
0.802	0.963	0.962
0.858	1.028	0.977
0.909	1.087	0.992
0.958	1.132	1.008
1.015	1.182	1.023
1.067	1.240	1.038
1.127	1.287	1.054
1.180	1.326	1.069
1.233	1.363	1.084
1.291	1.413	1.099
1.343	1.458	1.115
1.396	1.483	1.130
1.451	1.520	1.145
1.506	1.554	1.160
1.562	1.582	1.176
1.615	1.616	1.191
1.666	1.635	1.206
1.727	1.656	1.222
1.780	1.674	1.237

Contact

x (m)	z (m)	t (s)
1.835	1.700	1.252
1.889	1.716	1.267
1.936	1.729	1.283
1.996	1.747	1.298
2.044	1.768	1.314
2.091	1.789	1.329
2.146	1.804	1.344
2.194	1.819	1.360
2.239	1.842	1.375
2.285	1.873	1.391
2.320	1.892	1.406
2.370	1.913	1.422
2.407	1.935	1.437
2.448	1.961	1.452
2.493	1.978	1.468
2.528	1.995	1.483
2.570	2.014	1.499

Postflight

x (m)	z (m)	t (s)
2.605	2.026	1.514
2.646	2.052	1.529
2.689	2.055	1.545
2.728	2.071	1.560
2.773	2.076	1.576
2.810	2.086	1.591
2.850	2.090	1.606
2.897	2.094	1.622
2.931	2.091	1.637
2.983	2.096	1.653
3.022	2.088	1.668
3.068	2.084	1.683
3.111	2.079	1.699
3.151	2.070	1.714
3.197	2.056	1.730
3.243	2.037	1.745
3.281	2.026	1.760
3.331	2.009	1.776
3.376	1.983	1.791
3.415	1.965	1.807
3.467	1.940	1.822
3.508	1.908	1.838
3.547	1.872	1.853
3.601	1.841	1.868
3.639	1.805	1.884
3.690	1.767	1.899
3.734	1.725	1.915
3.775	1.688	1.930
3.824	1.639	1.945
3.903	1.608	1.961
3.906	1.543	1.976
3.955	1.487	1.991
3.993	1.433	2.007
4.040	1.375	2.022
4.079	1.319	2.038
4.118	1.255	2.053
4.163	1.196	2.067
4.200	1.134	2.084

JBHSF

Preflight

x (m)	z (m)	t (s)
1.072	1.001	0.448
1.136	1.062	0.463
1.195	1.119	0.478
1.255	1.175	0.494
1.308	1.227	0.509
1.375	1.272	0.524
1.438	1.325	0.539
1.500	1.379	0.554
1.566	1.415	0.569
1.628	1.459	0.584
1.688	1.506	0.600
1.757	1.539	0.615
1.822	1.564	0.630

Contact

x (m)	z (m)	t (s)
1.888	1.597	0.645
1.952	1.627	0.660
2.004	1.656	0.675
2.057	1.690	0.691
2.108	1.720	0.706
2.160	1.763	0.721
2.201	1.797	0.736
2.248	1.838	0.751
2.293	1.870	0.766
2.336	1.908	0.781
2.378	1.943	0.797
2.417	1.974	0.812
2.454	2.004	0.827

Postflight

x (m)	z (m)	t (s)
2.495	2.026	0.842
2.529	2.058	0.857
2.568	2.092	0.872
2.608	2.114	0.888
2.653	2.138	0.903
2.692	2.160	0.918
2.729	2.184	0.933
2.778	2.197	0.948
2.821	2.203	0.963
2.865	2.211	0.978
2.900	2.220	0.994
2.944	2.220	1.009
2.979	2.231	1.024
3.017	2.238	1.039
3.060	2.231	1.054
3.104	2.234	1.069
3.142	2.221	1.084
3.179	2.215	1.100
3.215	2.216	1.115
3.259	2.206	1.130
3.300	2.205	1.145
3.343	2.195	1.160
3.396	2.176	1.175
3.433	2.152	1.190
3.483	2.126	1.206
3.521	2.102	1.221
3.563	2.077	1.236
3.604	2.043	1.251
3.652	2.006	1.266
3.696	1.969	1.281
3.732	1.940	1.297
3.770	1.900	1.312
3.813	1.860	1.327
3.848	1.820	1.342
3.893	1.772	1.357
3.933	1.723	1.372
3.960	1.673	1.388
4.013	1.619	1.403
4.046	1.577	1.418
4.092	1.524	1.433
4.129	1.464	1.448
4.172	1.409	1.463
4.213	1.347	1.478
4.255	1.286	1.494
4.304	1.217	1.509
4.311	1.173	1.524
4.384	1.086	1.539
4.434	0.996	1.554

BSTV

Preflight

x (m)	z (m)	t (s)
1.536	1.413	0.527
1.580	1.450	0.542
1.659	1.503	0.556
1.718	1.557	0.571
1.777	1.589	0.586
1.851	1.638	0.601
1.911	1.660	0.615
1.972	1.697	0.630
2.047	1.726	0.645
2.100	1.766	0.659
2.173	1.774	0.674
2.239	1.803	0.689
2.290	1.822	0.704
2.362	1.850	0.718
2.427	1.874	0.733
2.510	1.882	0.748
2.553	1.894	0.763
2.620	1.908	0.777

Contact

x (m)	z (m)	t (s)
2.675	1.903	0.792
2.809	1.928	0.821
2.922	1.957	0.849
3.020	1.999	0.878
3.123	2.048	0.906
3.241	2.076	0.935
3.333	2.116	0.963

Postflight

x (m)	z (m)	t (s)
3.365	2.136	0.992
3.444	2.147	1.006
3.508	2.170	1.020
3.455	2.152	1.035
3.609	2.164	1.049
3.642	2.184	1.063
3.701	2.176	1.077
3.758	2.190	1.092
3.797	2.169	1.106
3.857	2.178	1.120
3.898	2.155	1.134
3.965	2.161	1.149
4.016	2.141	1.163
4.081	2.125	1.177
4.129	2.116	1.191
4.174	2.099	1.206
4.227	2.075	1.220
4.281	2.046	1.234
4.342	2.041	1.249
4.395	1.995	1.263
4.450	1.979	1.277
4.493	1.965	1.291
4.553	1.915	1.306
4.597	1.878	1.320
4.654	1.843	1.334
4.704	1.803	1.348
4.752	1.763	1.363
4.805	1.725	1.377
4.855	1.674	1.391
4.901	1.632	1.406
4.950	1.577	1.420
5.017	1.517	1.434
5.062	1.458	1.448
5.119	1.389	1.463
5.165	1.337	1.477

SCH

Preflight

x (m)	z (m)	t (s)
1.323	1.598	0.867
1.383	1.647	0.882
1.444	1.702	0.897
1.505	1.755	0.912
1.567	1.799	0.927
1.624	1.849	0.942
1.683	1.897	0.957
1.737	1.941	0.972
1.799	1.979	0.987
1.858	2.024	1.002
1.920	2.055	1.017
1.973	2.088	1.032
2.035	2.125	1.047
2.100	2.153	1.062
2.159	2.178	1.077
2.223	2.196	1.092
2.280	2.220	1.107
2.339	2.239	1.122

Contact

x (m)	z (m)	t (s)
2.393	2.250	1.137
2.452	2.271	1.152
2.507	2.288	1.167
2.563	2.307	1.182
2.617	2.326	1.197
2.669	2.348	1.214
2.713	2.373	1.226
2.755	2.399	1.241
2.804	2.415	1.256
2.848	2.447	1.271
2.893	2.472	1.286
2.929	2.493	1.301
2.971	2.512	1.316
3.015	2.533	1.331
3.055	2.554	1.345

Postflight

x (m)	z (m)	t (s)
3.099	2.570	1.360
3.136	2.591	1.375
3.177	2.608	1.390
3.225	2.616	1.405
3.267	2.635	1.420
3.305	2.631	1.435
3.348	2.643	1.450
3.390	2.644	1.465
3.436	2.647	1.480
3.472	2.647	1.494
3.518	2.648	1.509
3.565	2.638	1.524
3.610	2.640	1.539
3.658	2.627	1.554
3.692	2.621	1.569
3.739	2.600	1.584
3.783	2.578	1.599
3.828	2.551	1.613
3.864	2.540	1.628
3.911	2.518	1.643
3.949	2.493	1.658
3.994	2.470	1.673
4.029	2.437	1.688
4.070	2.403	1.703
4.123	2.390	1.718
4.161	2.346	1.733
4.205	2.313	1.747
4.244	2.273	1.762
4.287	2.230	1.777
4.330	2.185	1.792
4.345	2.162	1.807
4.413	2.086	1.822
4.451	2.039	1.837
4.490	1.982	1.852
4.533	1.926	1.867
4.571	1.865	1.881
4.614	1.810	1.896
4.649	1.753	1.911
4.688	1.697	1.926

AGY

Preflight

x (m)	z (m)	t (s)
2.072	1.548	0.435
2.141	1.604	0.450
2.193	1.660	0.465
2.247	1.708	0.479
2.313	1.752	0.494
2.368	1.794	0.509
2.429	1.842	0.524
2.496	1.882	0.539
2.557	1.924	0.554
2.620	1.965	0.569
2.686	1.999	0.583
2.743	2.022	0.598
2.801	2.064	0.613

Contact

x (m)	z (m)	t (s)
2.864	2.082	0.628
2.921	2.115	0.643
2.965	2.132	0.658
3.028	2.172	0.673
3.078	2.198	0.687
3.125	2.252	0.702
3.175	2.287	0.717
3.209	2.315	0.732
3.243	2.366	0.747
3.278	2.398	0.762
3.313	2.442	0.777
3.349	2.476	0.792
3.379	2.516	0.806
3.410	2.556	0.821
3.447	2.589	0.836
3.485	2.620	0.851

Postflight

x (m)	z (m)	t (s)
3.518	2.645	0.866
3.540	2.676	0.881
3.571	2.696	0.896
3.600	2.725	0.910
3.626	2.737	0.925
3.661	2.754	0.940
3.694	2.777	0.955
3.724	2.798	0.970
3.757	2.800	0.985
3.788	2.812	1.000
3.819	2.809	1.014
3.847	2.826	1.029
3.881	2.834	1.044
3.914	2.830	1.059
3.944	2.840	1.074
3.991	2.823	1.089
4.012	2.830	1.103
4.041	2.817	1.118
4.069	2.805	1.133
4.094	2.790	1.148
4.121	2.784	1.163
4.152	2.764	1.178
4.178	2.751	1.193
4.203	2.743	1.208
4.231	2.721	1.222
4.265	2.694	1.237
4.295	2.685	1.252
4.329	2.647	1.267
4.357	2.617	1.282
4.390	2.591	1.297
4.426	2.556	1.312
4.460	2.525	1.326
4.492	2.482	1.341
4.522	2.446	1.356
4.551	2.401	1.371
4.584	2.358	1.386
4.610	2.319	1.401
4.648	2.267	1.416
4.679	2.220	1.430
4.706	2.164	1.445
4.740	2.115	1.460
4.775	2.054	1.475
4.810	1.992	1.490
4.835	1.933	1.505
4.868	1.863	1.520
4.903	1.805	1.534
4.937	1.744	1.549
4.969	1.672	1.564

JTHH

Preflight

x (m)	z (m)	t (s)
0.992	1.632	0.603
1.056	1.691	0.617
1.117	1.746	0.632
1.173	1.789	0.646
1.233	1.835	0.661
1.301	1.879	0.676
1.358	1.932	0.690
1.417	1.966	0.705
1.479	2.006	0.719
1.545	2.048	0.734
1.607	2.079	0.748
1.661	2.115	0.763
1.727	2.148	0.778
1.785	2.177	0.792
1.849	2.203	0.807
1.921	2.233	0.821
1.981	2.249	0.836
2.045	2.268	0.850

Contact

x (m)	z (m)	t (s)
2.108	2.283	0.865
2.169	2.306	0.880
2.231	2.321	0.894
2.296	2.339	0.909
2.351	2.356	0.923
2.399	2.383	0.938
2.451	2.401	0.952
2.489	2.427	0.967
2.534	2.455	0.981
2.580	2.487	0.996
2.626	2.509	1.011
2.663	2.544	1.025
2.707	2.562	1.040
2.747	2.582	1.054
2.790	2.610	1.069
2.834	2.628	1.083

Postflight

x (m)	z (m)	t (s)
2.872	2.643	1.098
2.915	2.670	1.112
2.955	2.677	1.127
2.996	2.691	1.142
3.041	2.702	1.156
3.083	2.711	1.171
3.124	2.715	1.185
3.166	2.711	1.200
3.210	2.721	1.214
3.249	2.717	1.229
3.288	2.713	1.243
3.330	2.707	1.258
3.376	2.702	1.272
3.425	2.694	1.287
3.463	2.686	1.302
3.505	2.674	1.316
3.551	2.654	1.331
3.590	2.641	1.345
3.669	2.595	1.374
3.715	2.571	1.389
3.755	2.555	1.403
3.801	2.520	1.418
3.835	2.494	1.433
3.876	2.463	1.448
3.918	2.431	1.462
3.962	2.396	1.476
4.005	2.356	1.491
4.043	2.314	1.505
4.079	2.272	1.520
4.126	2.232	1.534
4.169	2.181	1.549
4.213	2.136	1.564
4.253	2.080	1.578
4.290	2.033	1.593
4.330	1.983	1.607
4.374	1.918	1.622
4.412	1.857	1.636
4.457	1.802	1.651
4.493	1.735	1.665

JTHL

Preflight

x (m)	z (m)	t (s)
1.386	1.847	0.184
1.445	1.894	0.199
1.515	1.944	0.213
1.580	1.992	0.228
1.646	2.031	0.242
1.714	2.074	0.256
1.777	2.119	0.271
1.849	2.149	0.285
1.921	2.177	0.300
1.988	2.220	0.314
2.057	2.246	0.328
2.125	2.280	0.343
2.198	2.316	0.357
2.265	2.335	0.372

Contact

x (m)	z (m)	t (s)
2.336	2.354	0.386
2.410	2.376	0.401
2.478	2.392	0.416
2.541	2.414	0.430
2.607	2.452	0.445
2.664	2.465	0.460
2.724	2.491	0.474
2.774	2.513	0.489
2.820	2.538	0.504
2.876	2.567	0.519
2.925	2.601	0.533
2.978	2.627	0.548
3.023	2.659	0.563
3.070	2.688	0.578
3.115	2.707	0.592
3.166	2.741	0.607
3.205	2.765	0.622
3.260	2.783	0.636
3.298	2.806	0.651
3.342	2.827	0.666

Postflight

x (m)	z (m)	t (s)
3.388	2.836	0.681
3.434	2.862	0.696
3.474	2.878	0.710
3.517	2.888	0.725
3.562	2.897	0.740
3.609	2.900	0.754
3.646	2.915	0.769
3.693	2.921	0.784
3.735	2.925	0.799
3.780	2.924	0.813
3.822	2.923	0.828
3.864	2.919	0.843
3.909	2.921	0.858
3.955	2.908	0.872
3.999	2.901	0.887
4.044	2.899	0.902
4.087	2.873	0.917
4.136	2.862	0.931
4.174	2.852	0.946
4.230	2.828	0.961
4.273	2.806	0.976
4.315	2.782	0.990
4.360	2.755	1.005
4.405	2.723	1.020
4.450	2.689	1.034
4.489	2.664	1.049
4.538	2.625	1.064
4.587	2.588	1.079
4.629	2.550	1.093
4.669	2.504	1.108
4.718	2.466	1.123
4.760	2.420	1.138
4.805	2.369	1.152
4.862	2.313	1.167
4.894	2.269	1.182
4.945	2.218	1.197
4.985	2.161	1.211
5.026	2.101	1.226
5.074	2.040	1.241
5.122	1.973	1.256
5.154	1.914	1.270

JTTVH

Preflight

x (m)	z (m)	t (s)
1.081	1.722	0.679
1.142	1.764	0.693
1.210	1.815	0.708
1.267	1.848	0.723
1.322	1.892	0.738
1.385	1.923	0.752
1.446	1.951	0.767
1.506	1.982	0.782
1.573	2.016	0.796
1.634	2.034	0.811
1.693	2.062	0.826
1.755	2.080	0.840

Contact

x (m)	z (m)	t (s)
1.821	2.106	0.855
1.876	2.122	0.870
1.933	2.158	0.884
1.985	2.173	0.899
2.040	2.205	0.913
2.133	2.242	0.942
2.266	2.341	0.987
2.314	2.368	1.001
2.356	2.393	1.016
2.397	2.421	1.031

Postflight

x (m)	z (m)	t (s)
2.448	2.450	1.045
2.494	2.475	1.060
2.541	2.486	1.075
2.583	2.498	1.089
2.626	2.518	1.104
2.671	2.533	1.119
2.720	2.554	1.133
2.762	2.555	1.148
2.812	2.562	1.163
2.854	2.566	1.178
2.897	2.569	1.192
2.942	2.577	1.207
2.990	2.579	1.222
3.041	2.570	1.236
3.085	2.563	1.251
3.135	2.561	1.266
3.182	2.550	1.280
3.229	2.546	1.295
3.284	2.530	1.310
3.319	2.509	1.324
3.369	2.492	1.339
3.417	2.467	1.354
3.461	2.444	1.369
3.502	2.419	1.383
3.546	2.394	1.398
3.589	2.368	1.413
3.632	2.343	1.427
3.670	2.302	1.442
3.717	2.274	1.457
3.758	2.236	1.471
3.799	2.191	1.486
3.845	2.153	1.501
3.888	2.115	1.515
3.927	2.058	1.530
3.973	2.016	1.545
4.019	1.968	1.560
4.060	1.912	1.574
4.104	1.857	1.589

JTTVL

Preflight

x (m)	z (m)	t (s)
0.461	1.130	0.797
0.521	1.171	0.812
0.578	1.210	0.827
0.646	1.243	0.842
0.706	1.278	0.857
0.757	1.303	0.872
0.815	1.331	0.887
0.875	1.361	0.902
0.937	1.379	0.917

Contact

x (m)	z (m)	t (s)
0.997	1.408	0.932
1.056	1.436	0.947
1.114	1.455	0.962
1.161	1.489	0.977
1.211	1.510	0.992
1.255	1.541	1.007
1.310	1.572	1.022
1.355	1.589	1.037
1.402	1.621	1.052
1.448	1.652	1.067
1.499	1.672	1.082
1.541	1.701	1.097
1.591	1.730	1.112

Postflight

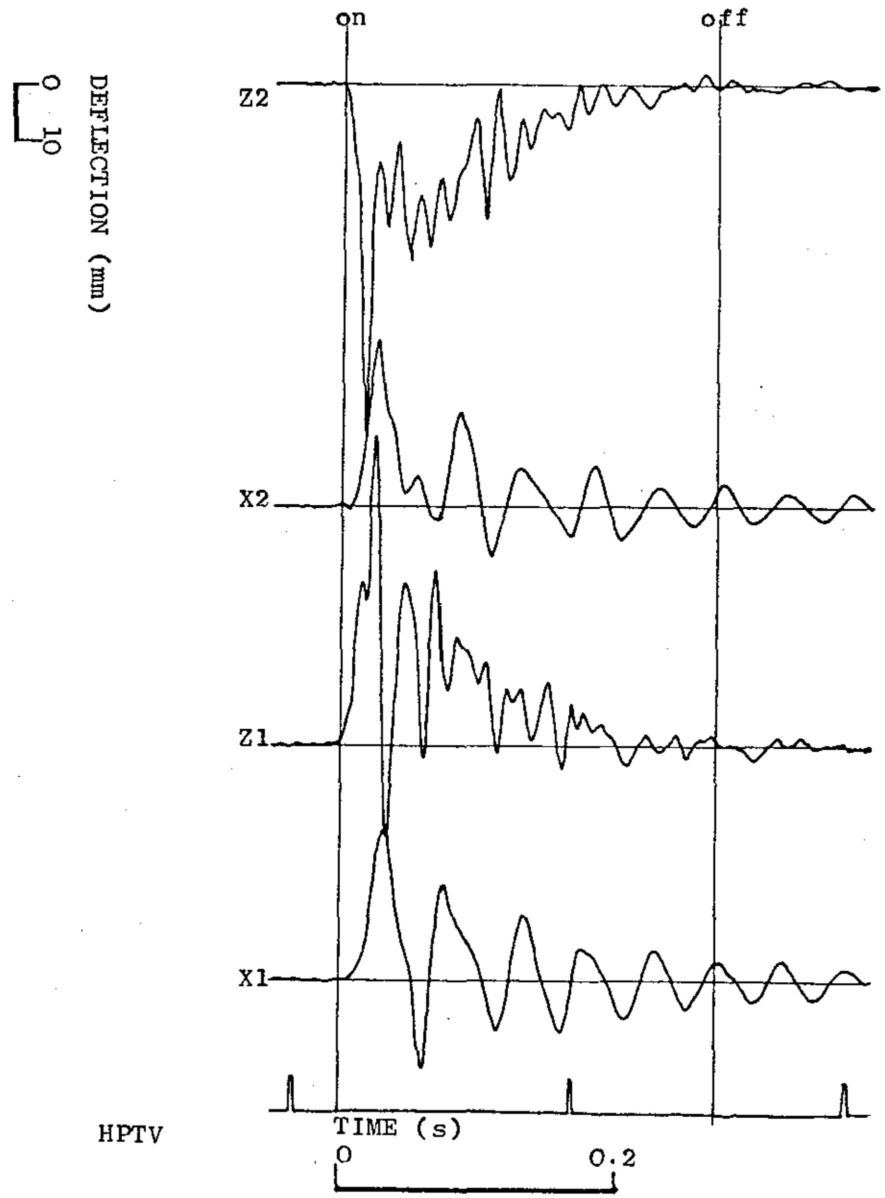
x (m)	z (m)	t (s)
1.631	1.750	1.127
1.677	1.770	1.142
1.721	1.792	1.157
1.769	1.804	1.172
1.816	1.817	1.187
1.855	1.835	1.202
1.904	1.848	1.217
1.951	1.850	1.232
1.992	1.854	1.247
2.037	1.858	1.262
2.086	1.867	1.277
2.135	1.863	1.292
2.181	1.862	1.307
2.219	1.861	1.322
2.264	1.846	1.337
2.309	1.837	1.352
2.354	1.828	1.367
2.396	1.811	1.382
2.443	1.793	1.397
2.486	1.780	1.412
2.531	1.766	1.427
2.570	1.740	1.442
2.614	1.716	1.457
2.658	1.690	1.472
2.702	1.659	1.487
2.745	1.629	1.502
2.788	1.603	1.517
2.834	1.570	1.532
2.874	1.535	1.547
2.916	1.490	1.562
2.956	1.455	1.577
3.003	1.416	1.592
3.055	1.366	1.607
3.092	1.322	1.622
3.134	1.270	1.637
3.179	1.219	1.652

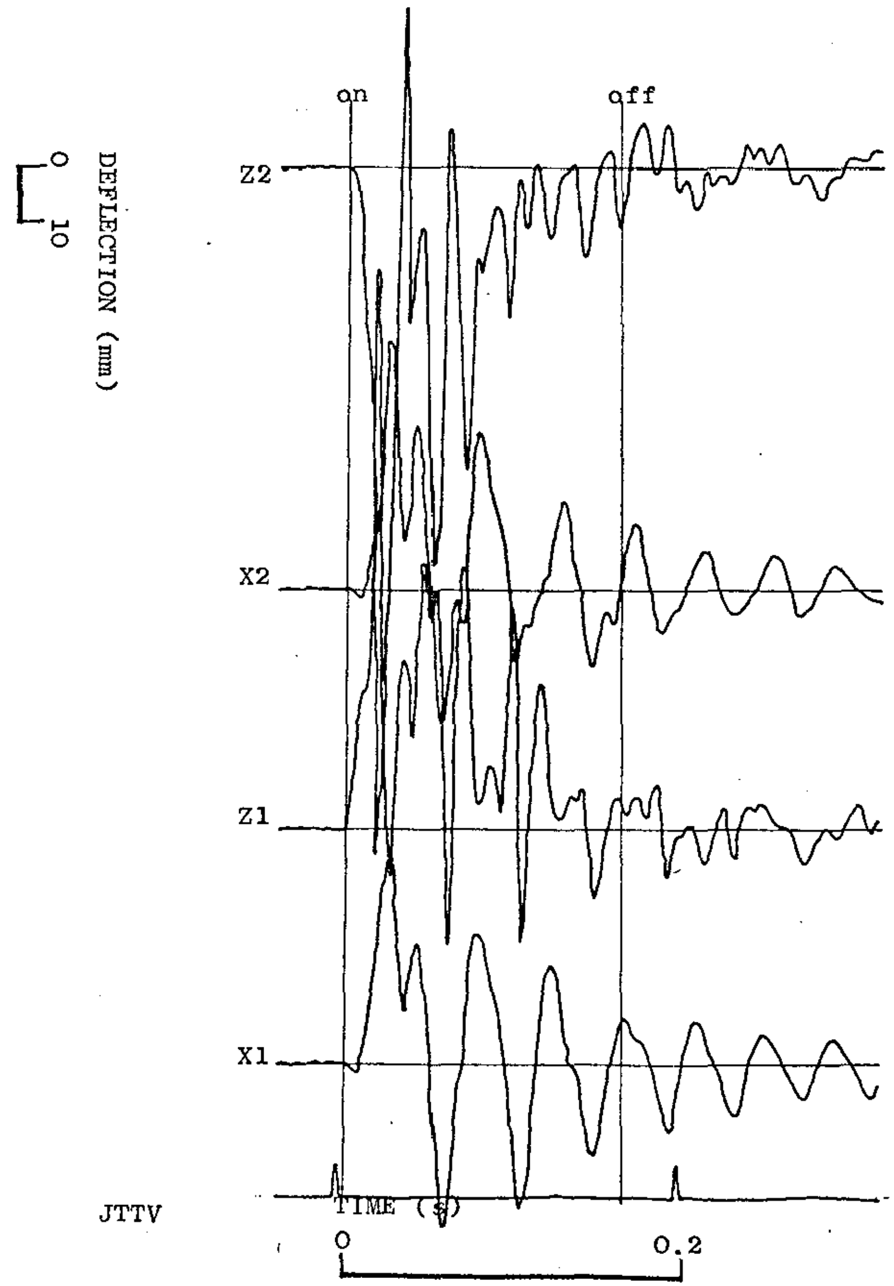
APPENDIX C

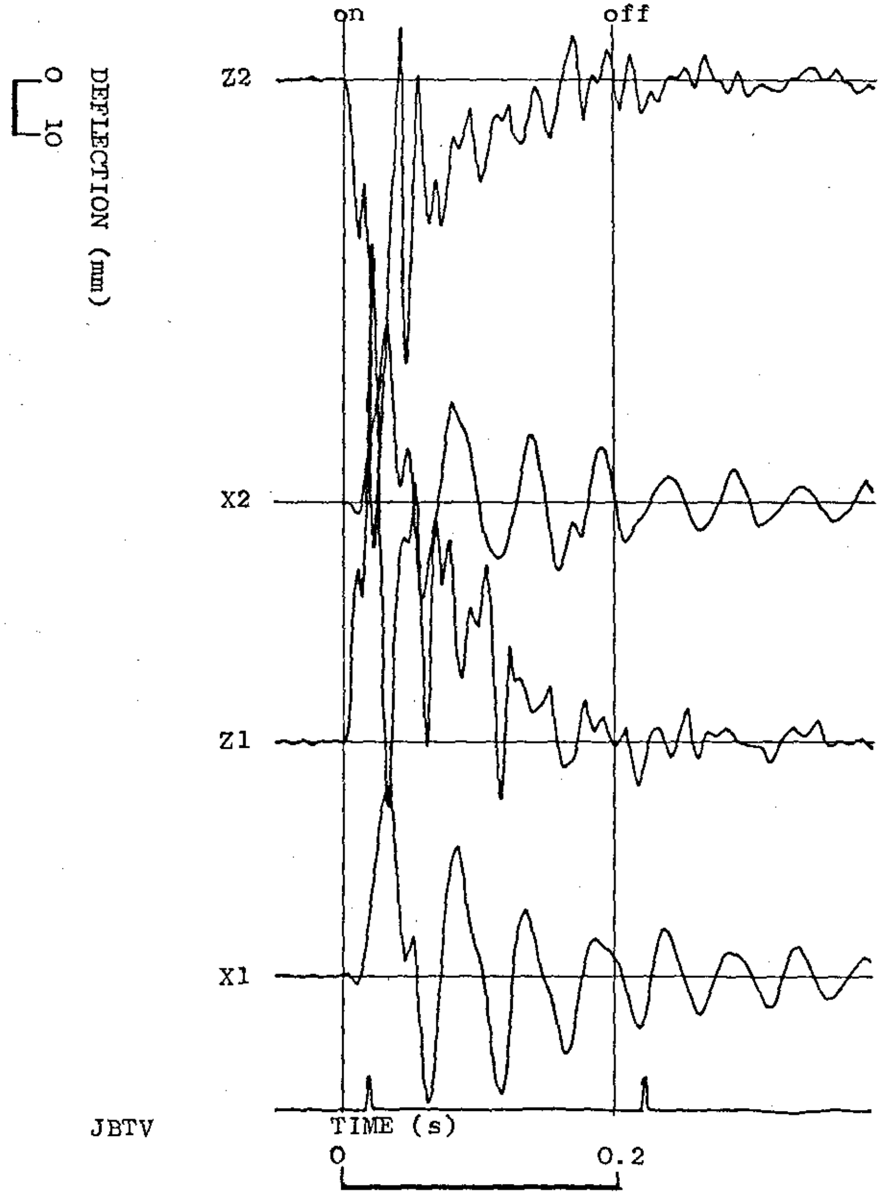
Force trace records.

Note: The force traces from each of the two platforms for each vault for all six subjects of Experiment 1 are presented.

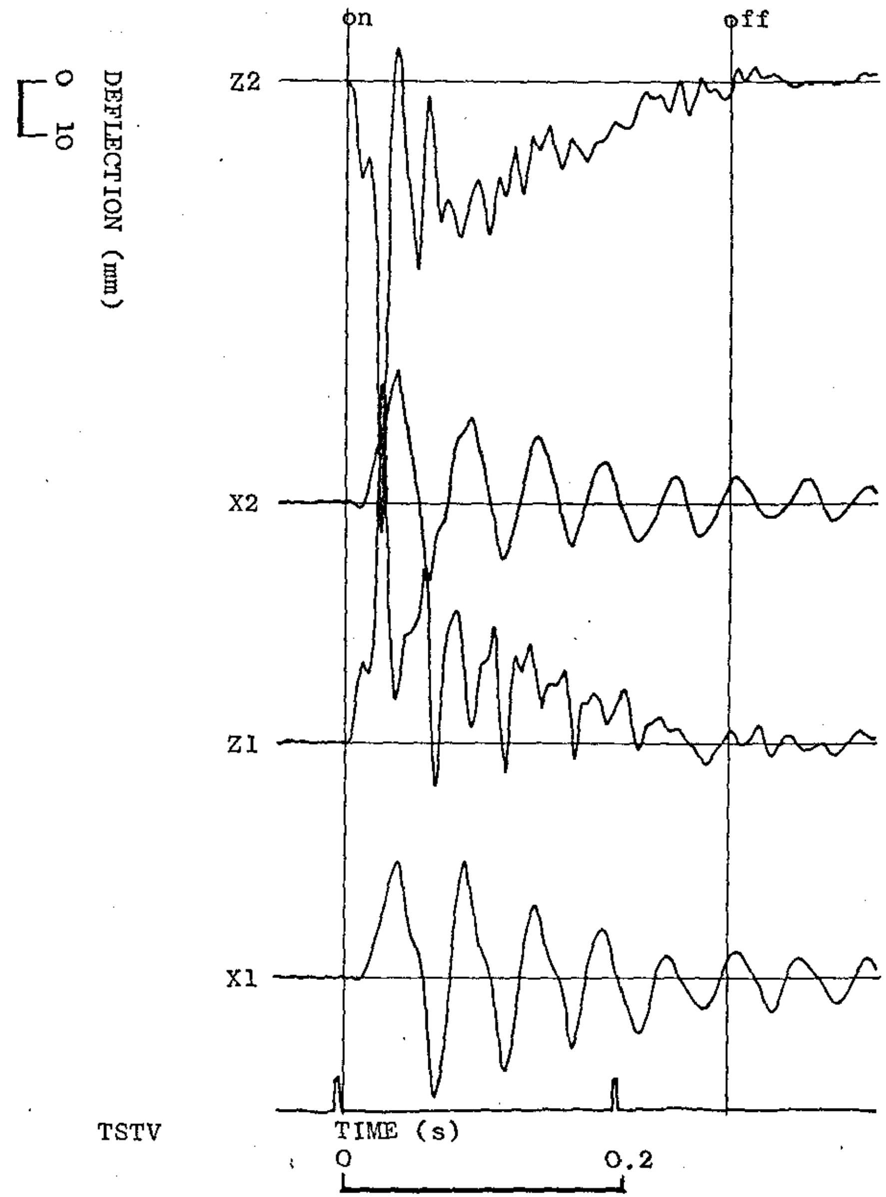
The calibration displacements are indicated in 10mm units, where 10mm is approximately equal to 40lbs. vertically and 65lbs. horizontally. Exact calibration curves (presented in Chapter 3) were used in the analysis. The upper trace, Z2, represents the vertical force of platform two from the moment of contact at the line marked "on", to the moment of departure indicated by the line across the trace. Trace X2 represents the horizontal force of platform two while Z1 and X1 represent the vertical and horizontal forces of platform one.


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
HPTV
TIME (s)
0
0.2

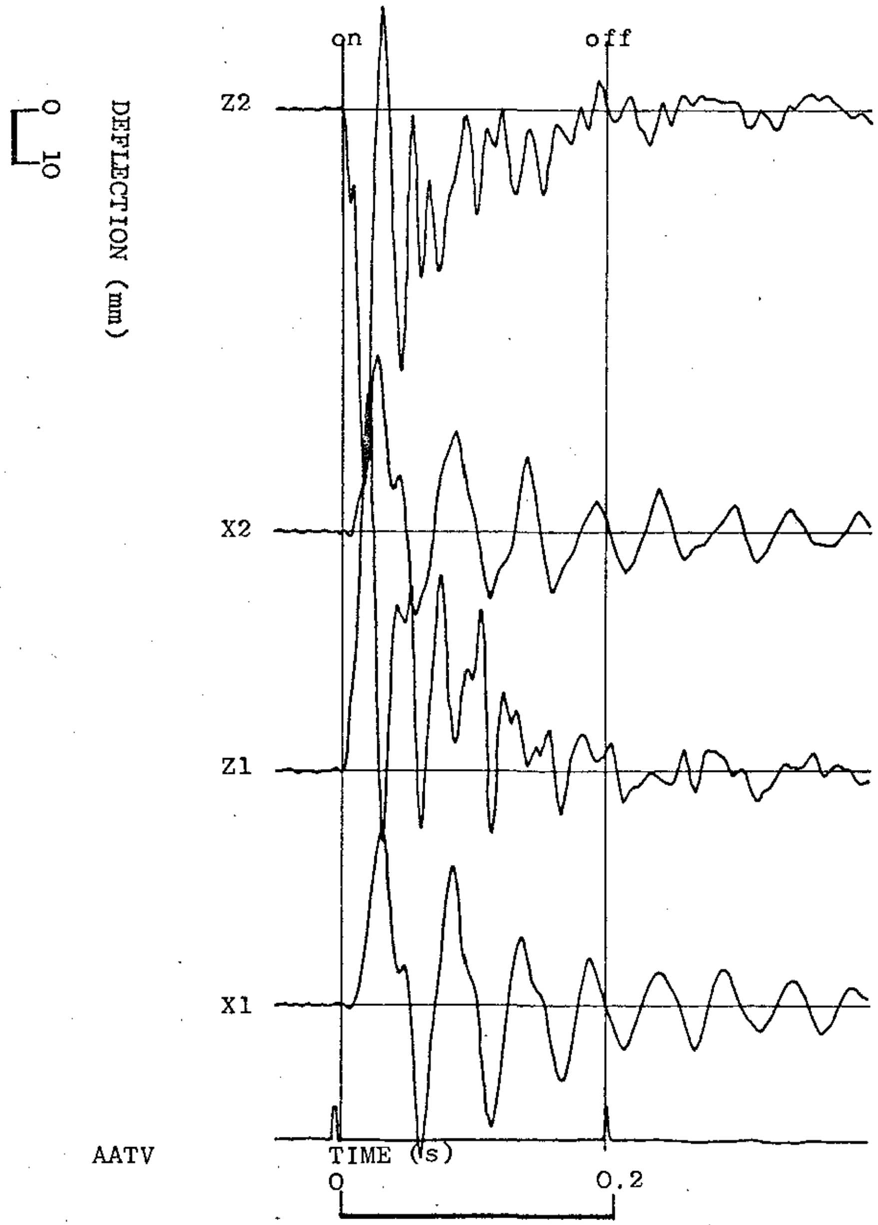

DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
JTTV
TIME (s)
0
0.2


on
off
Z2
X2
Z1
X1
0 10
DEFLECTION (mm)
TIME (s)
0
0.2

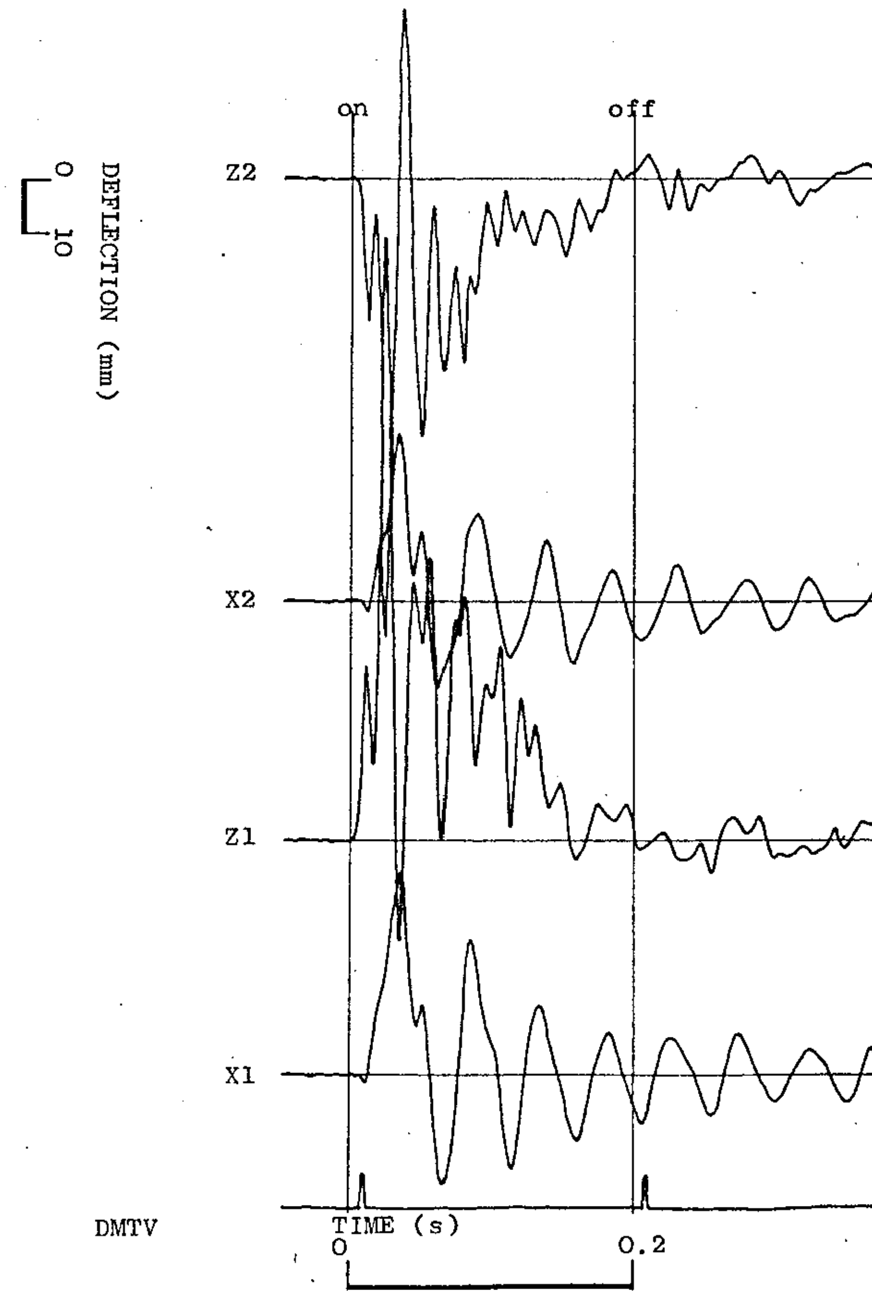
JBTV


on
off
Z2
X2
Z1
X1
0 10
DEFLECTION (mm)
TIME (s)
0
0.2

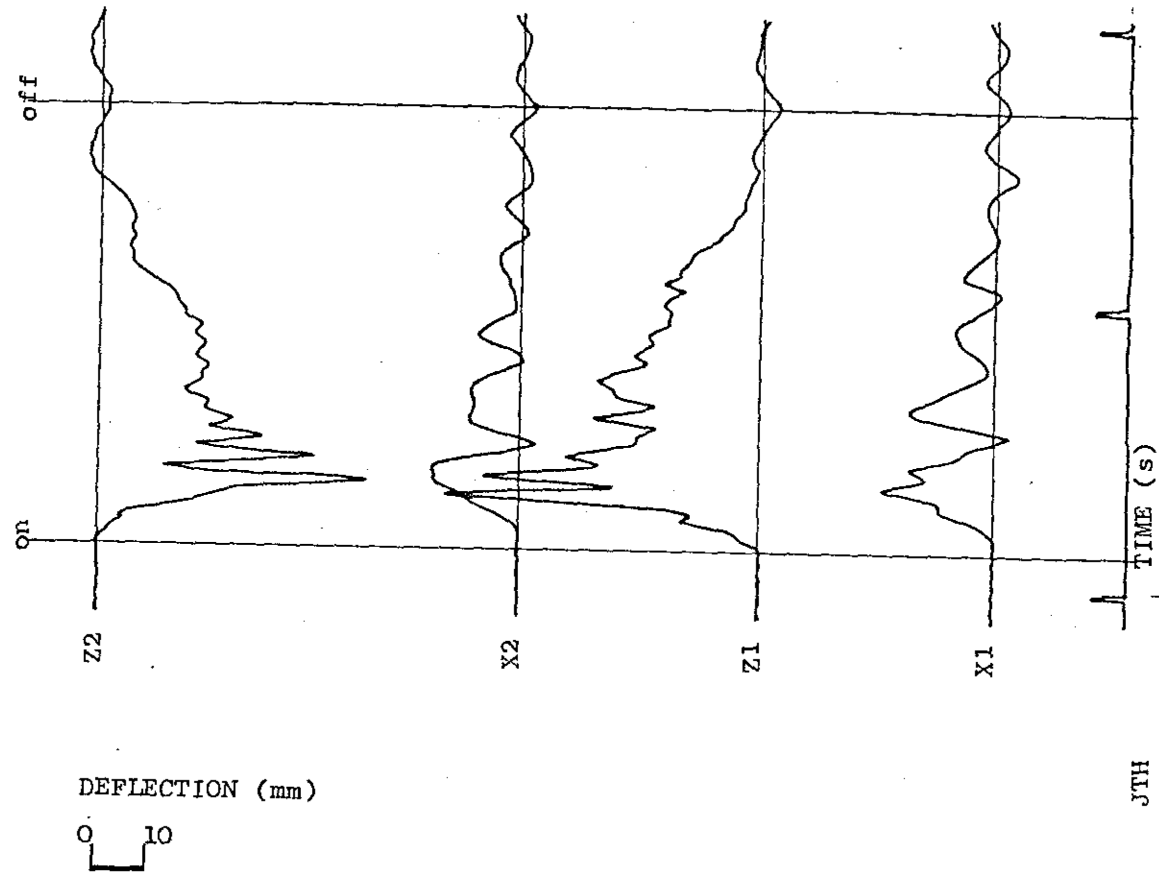
TSTV

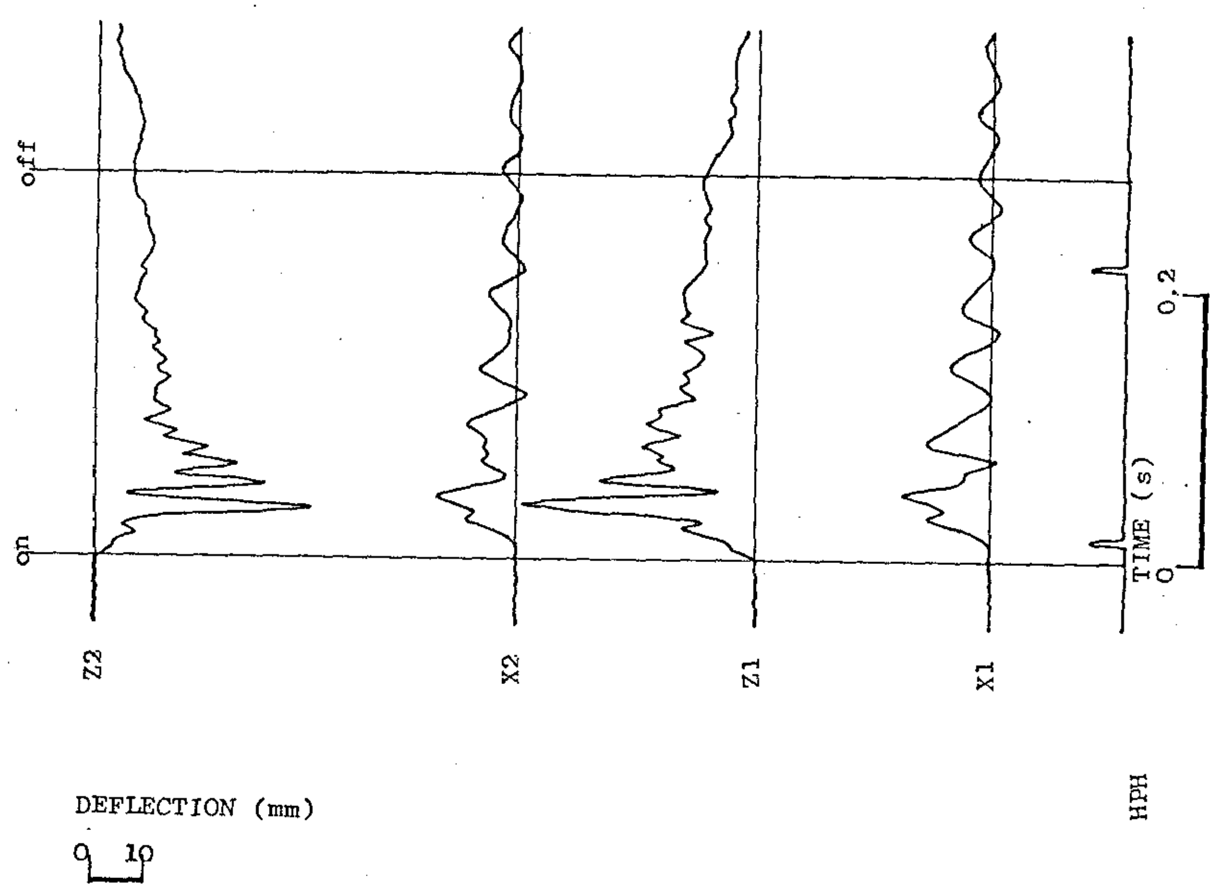

0
10
DEFLECTION (mm)
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

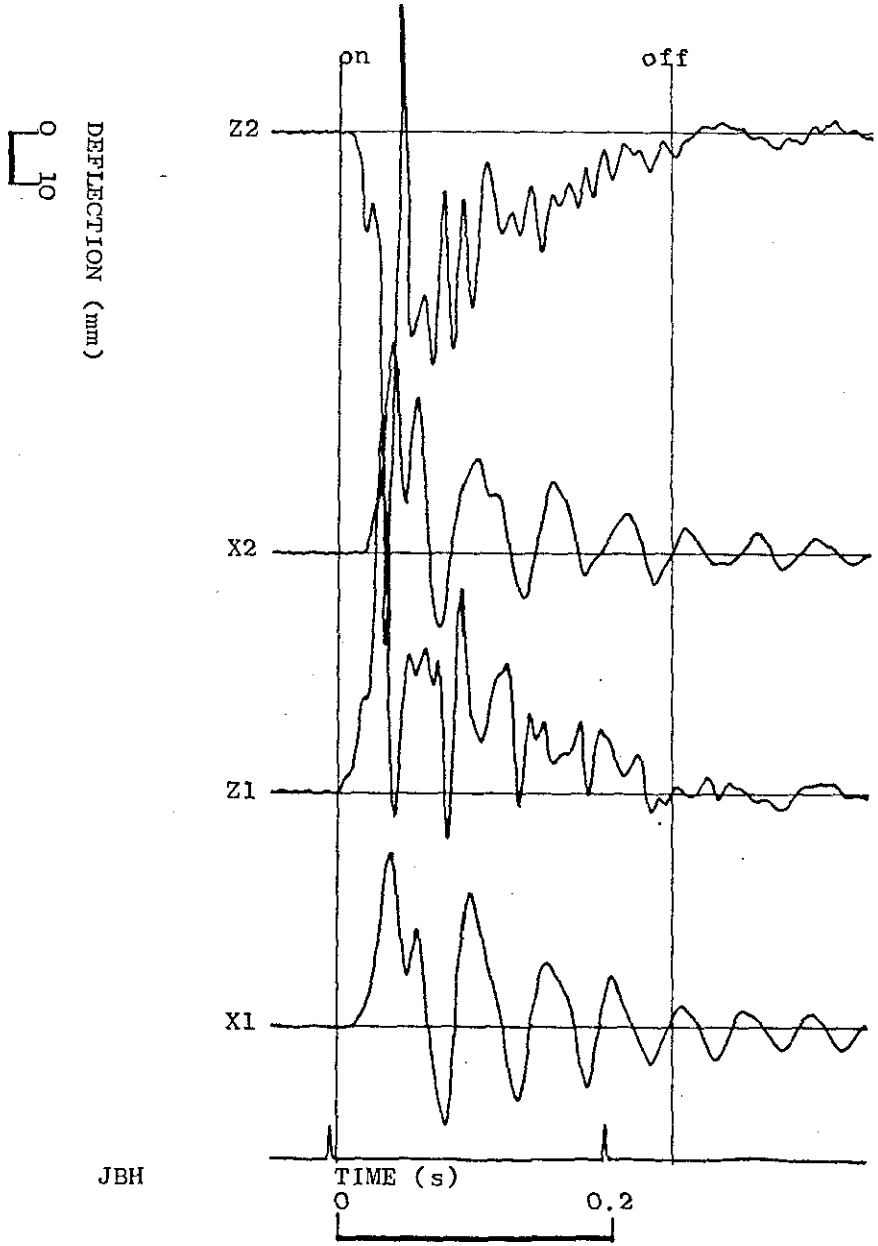
AATV


0
10
DEFLECTION (mm)
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

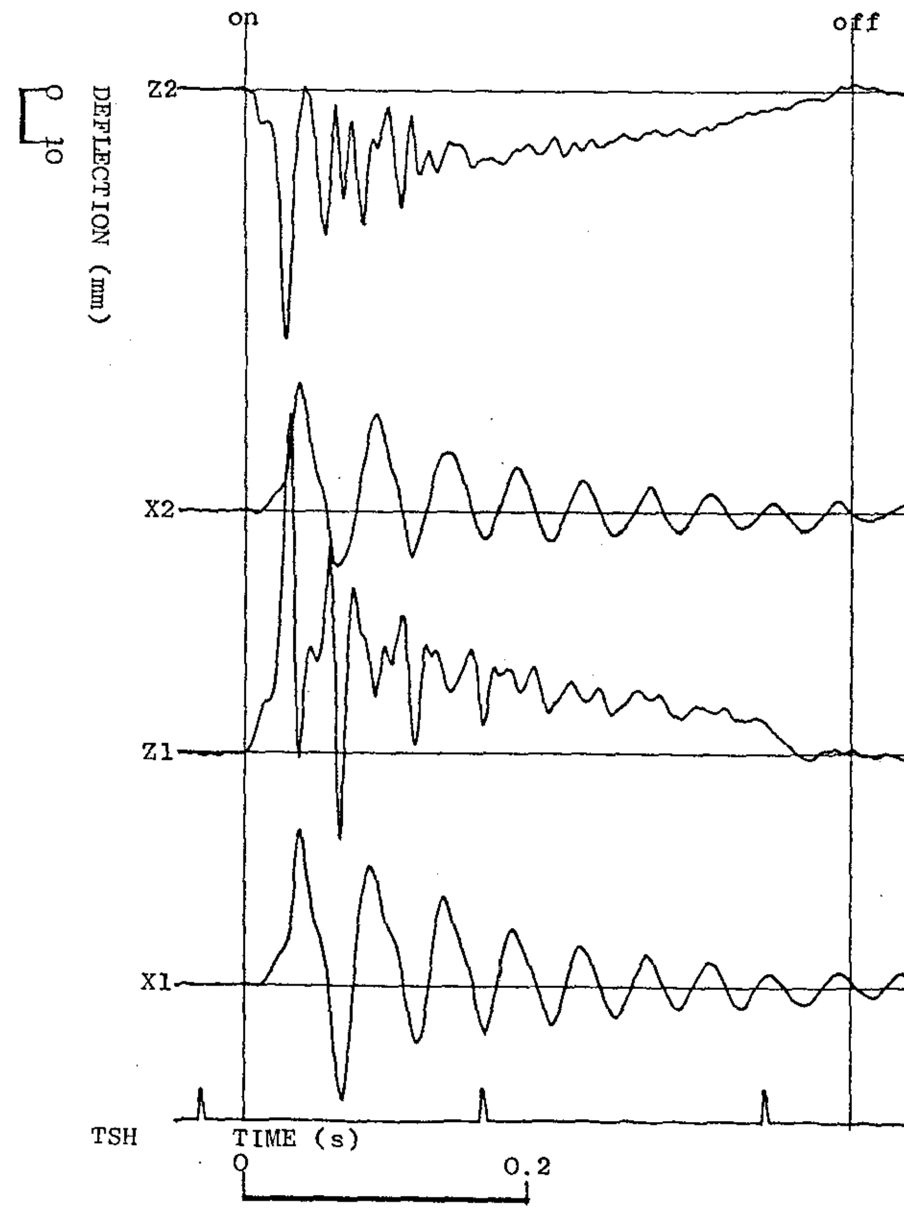
DMTV


on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2
DEFLECTION (mm)
0
10
JTH

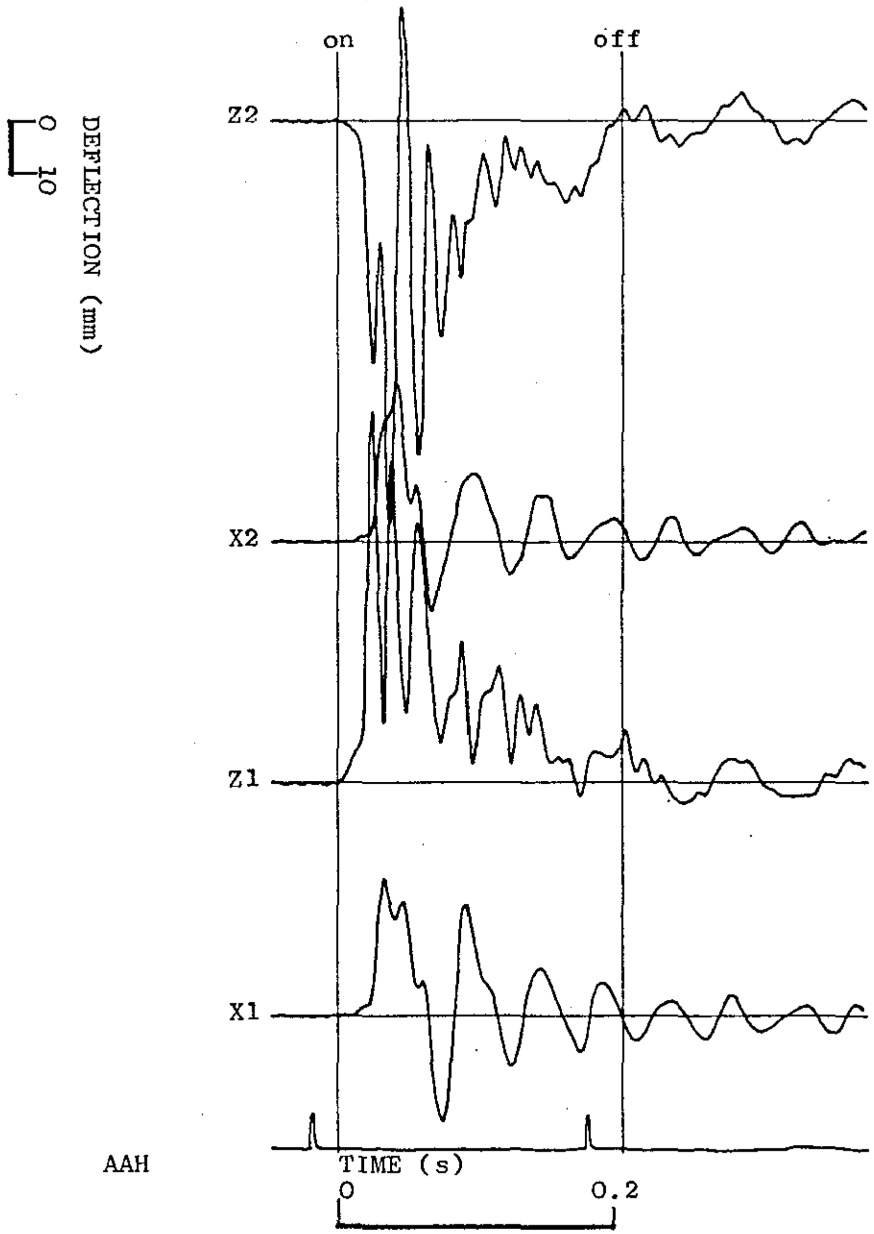

on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2
DEFLECTION (mm)
0
10
HPH


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

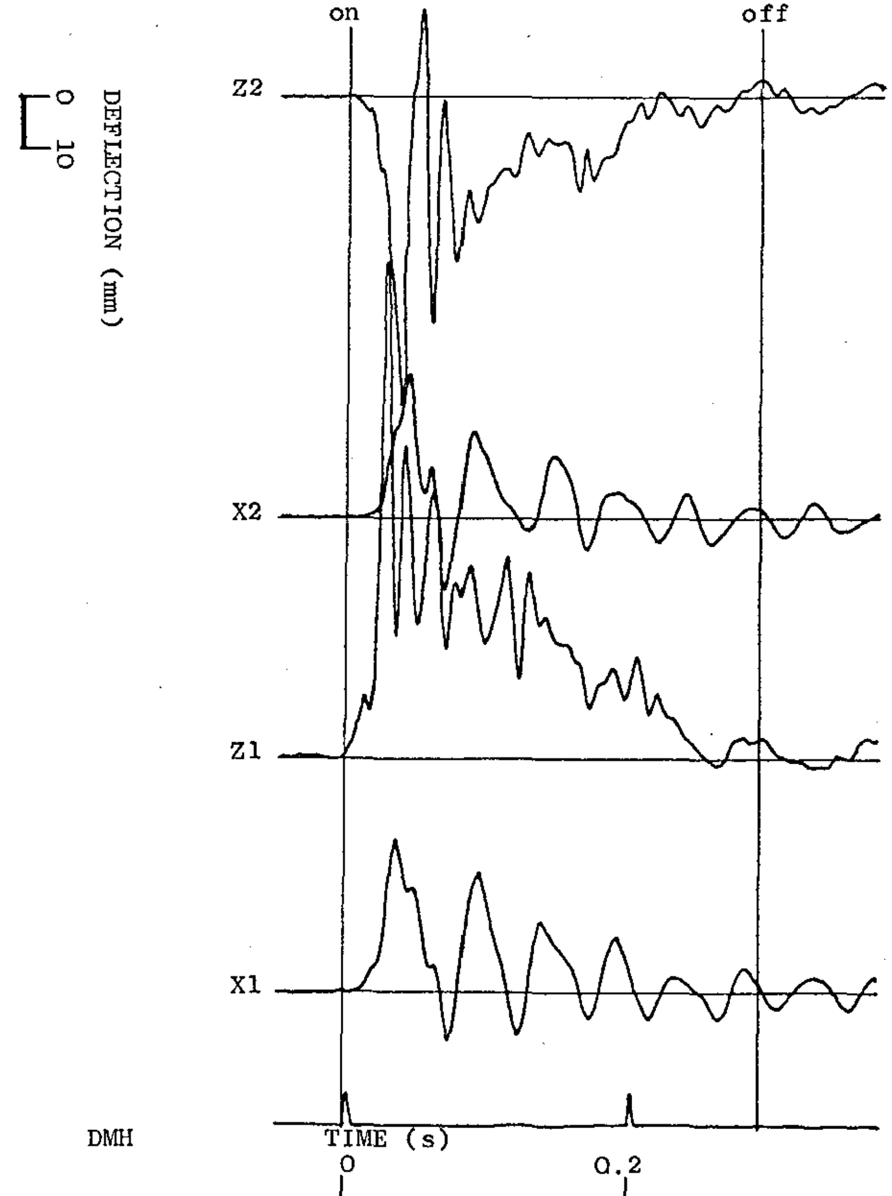
JBH


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

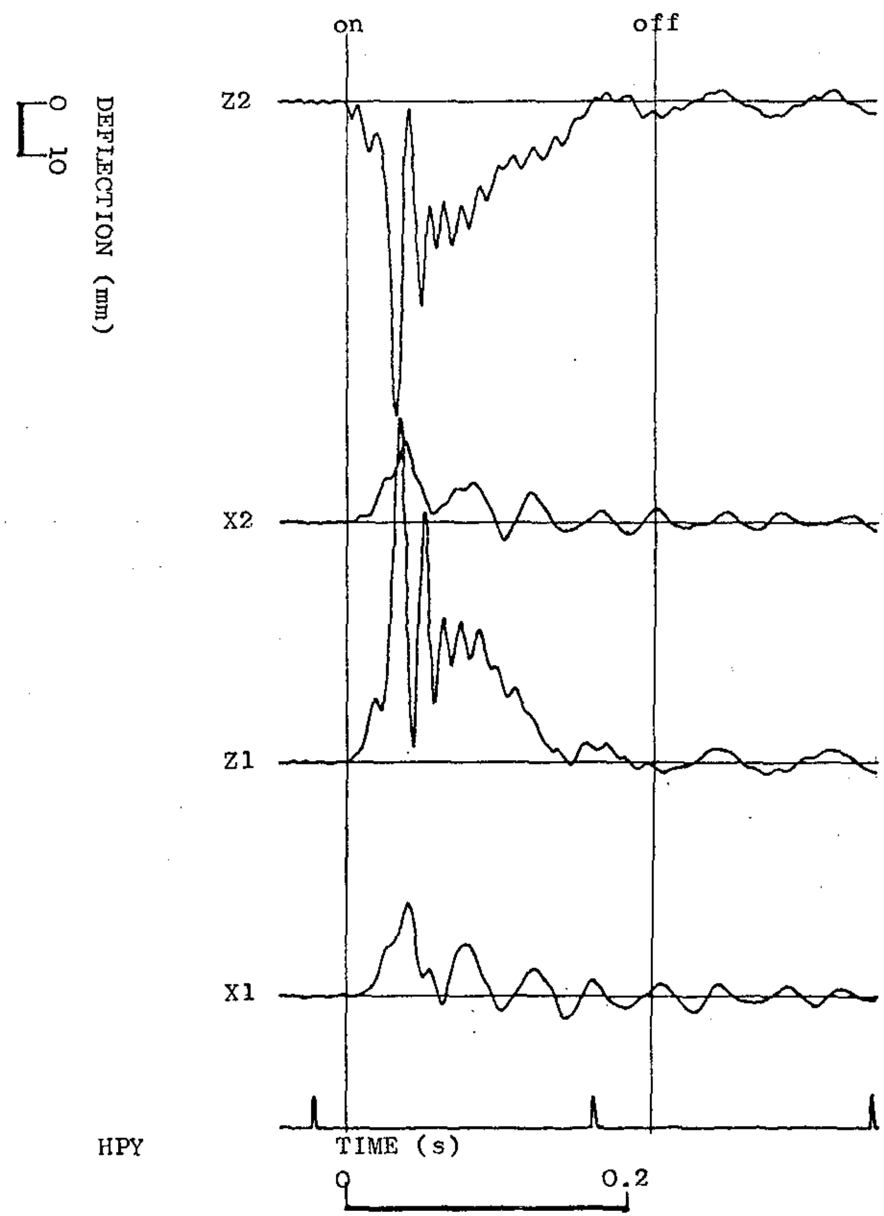
TSH


on
off
Z2
X2
Z1
X1
DEFLECTION (mm)
0 10
TIME (s)
0
0.2

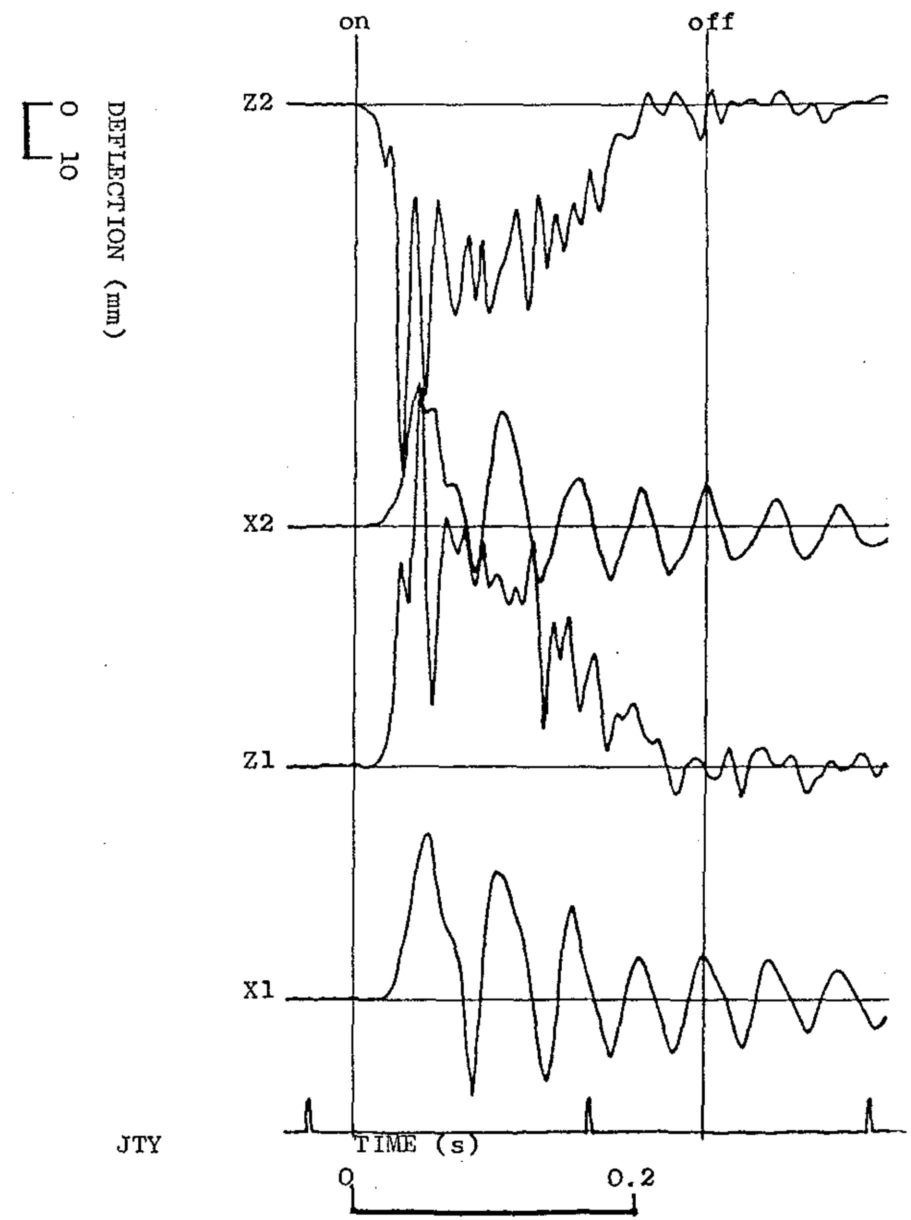
AAH


on
off
Z2
X2
Z1
X1
DEFLECTION (mm)
0 10
TIME (s)
0
0.2

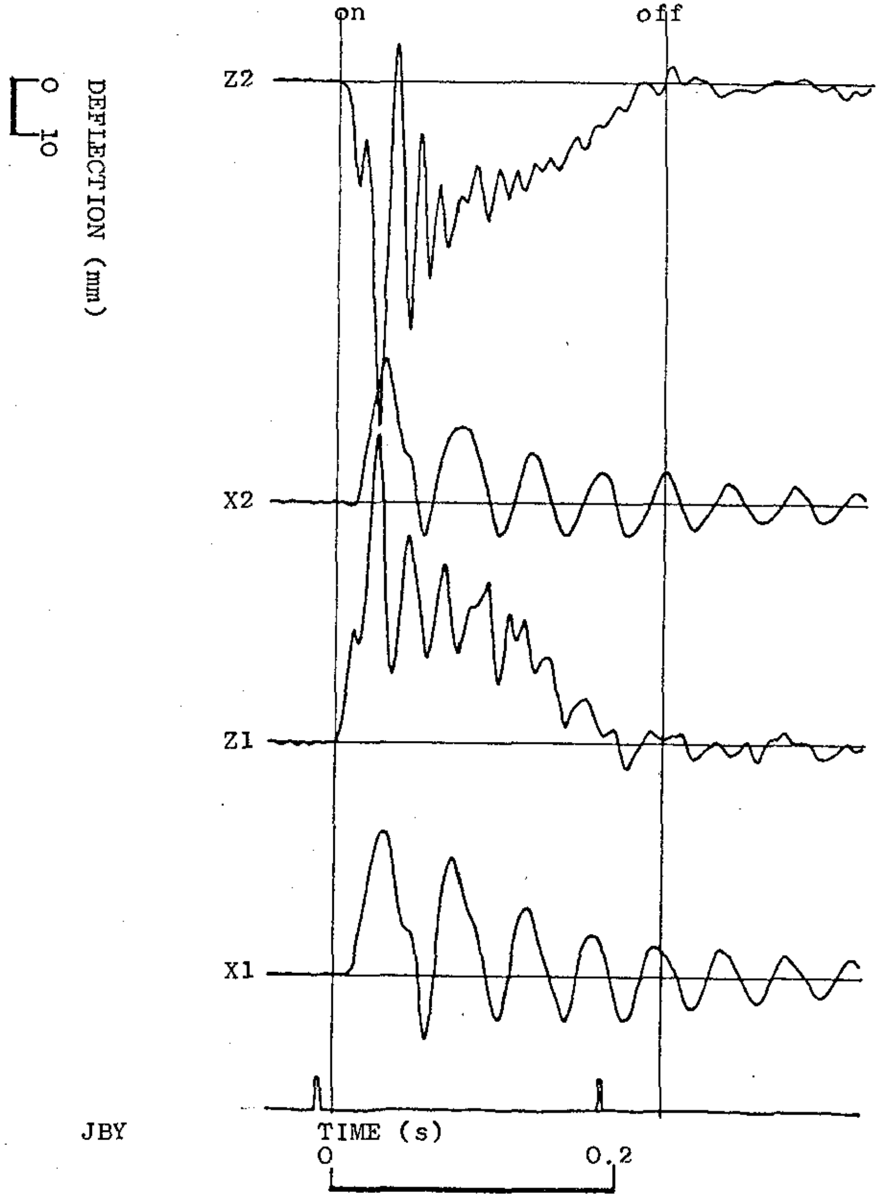
DMH

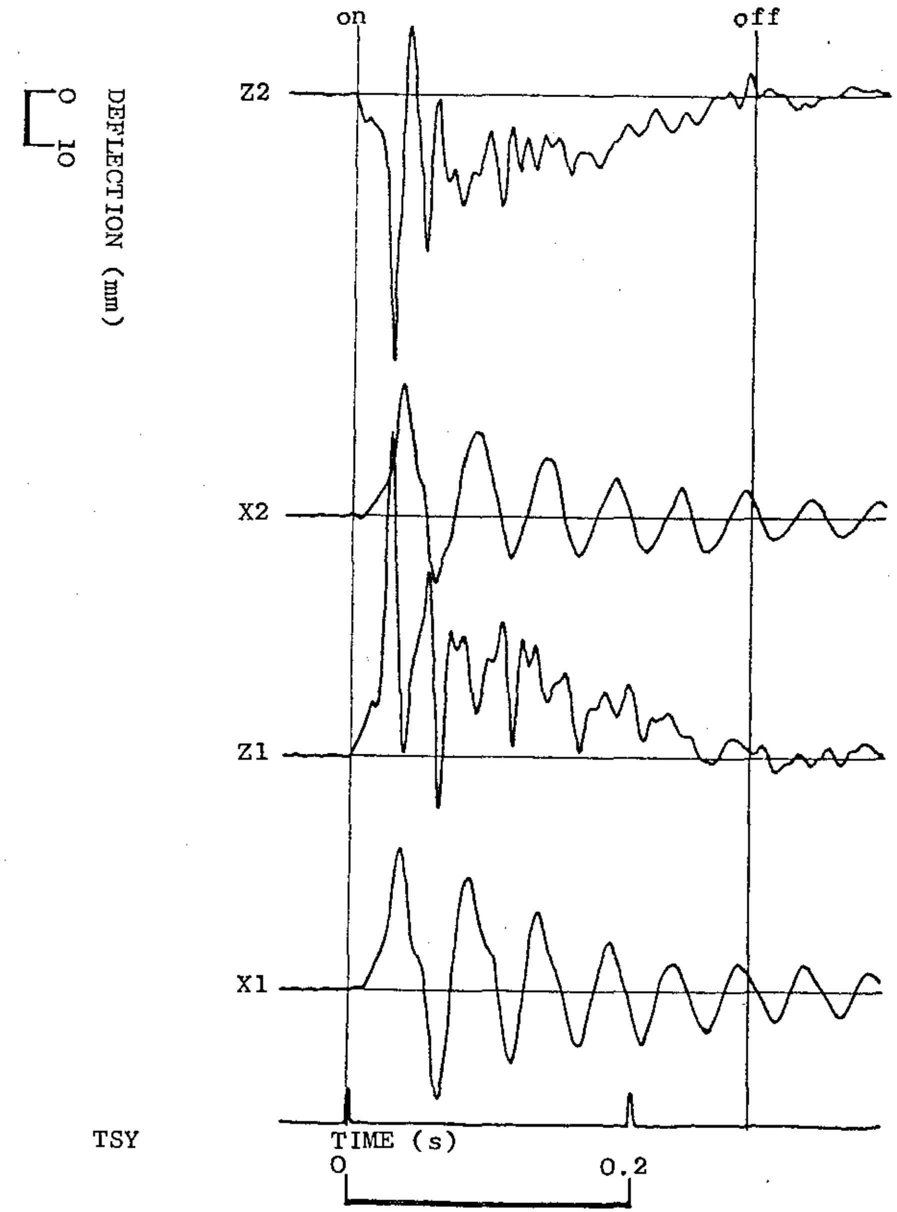

DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

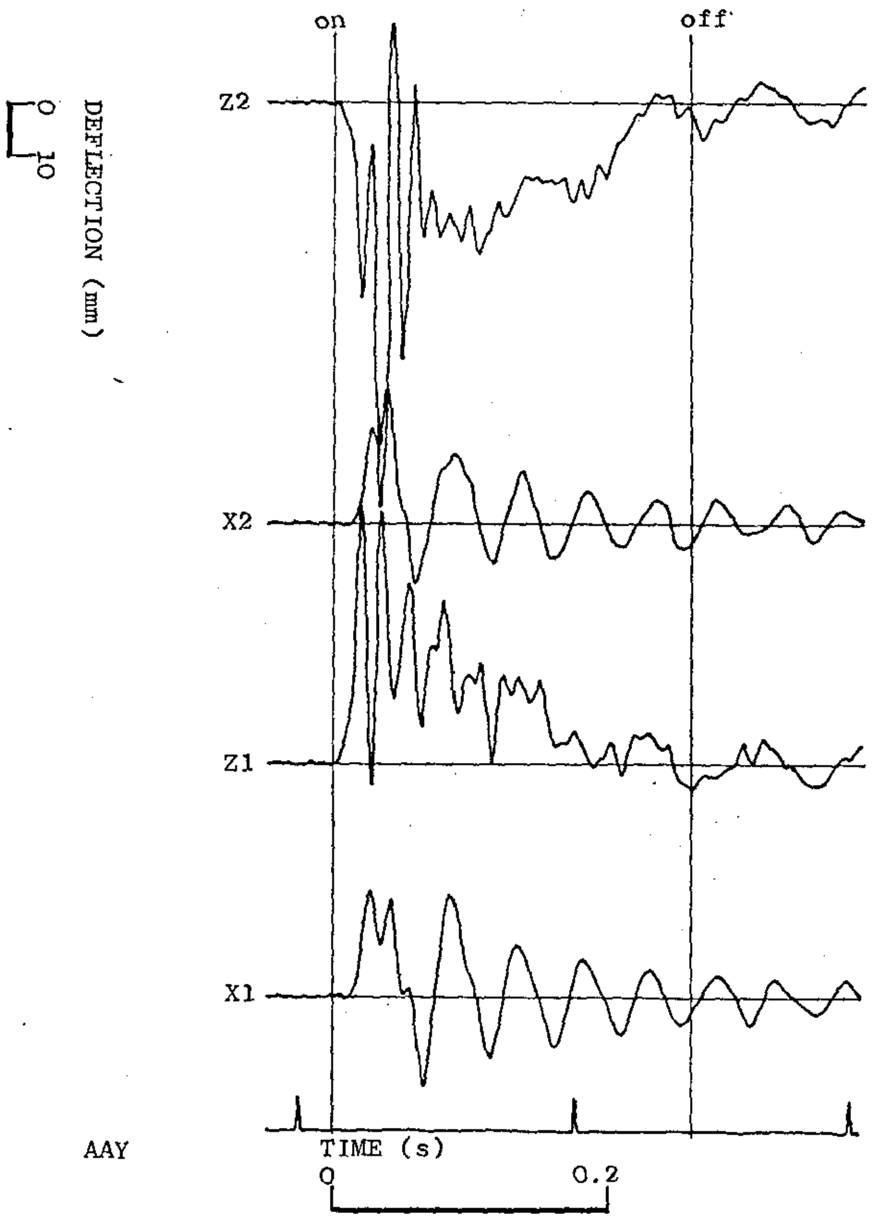
HPY


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
TIME (s)
0
0.2

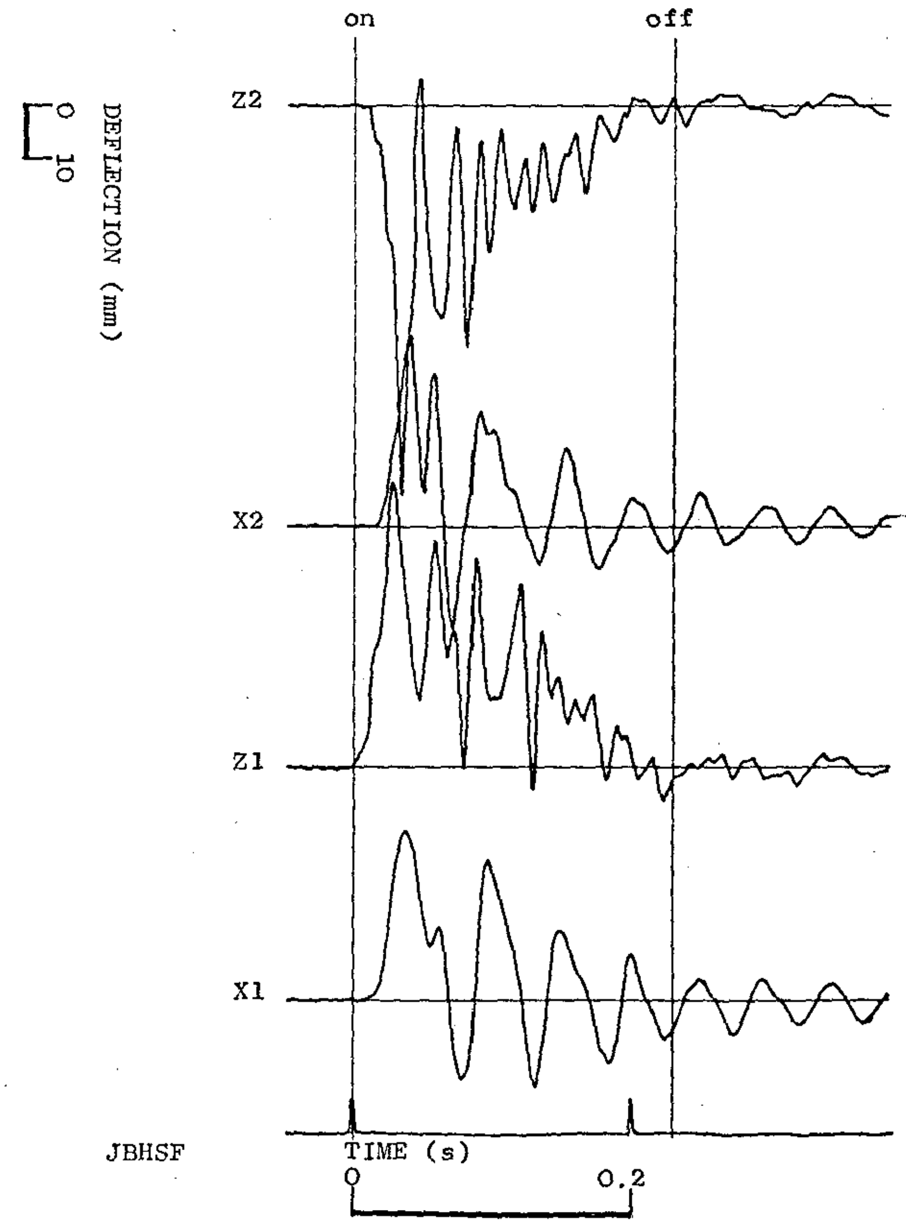
JTY


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
JBY
TIME (s)
0
0.2


DEFLECTION (mm)
0
10
on
off
Z2
X2
Z1
X1
TSY
TIME (s)
0
0.2



0
10
DEFLECTION (mm)
on
off
Z2
X2
Z1
X1
AAY
TIME (s)
0
0.2



0
10
DEFLECTION (mm)
on
off
Z2
X2
Z1
X1
JBHSF
TIME (s)
0
0.2

APPENDIX D.

Derived kinematic and kinetic data.

Note: The kinematic and kinetic data for all six subjects taking part in the first experiment for each vault are presented here (pages 230 - 235). The kinematic data for the four subjects in the second experiment are also presented (pages 236 - 237).

Each vault is labelled at the head of the right hand series of columns (HPTV = HP (subject): layout squat vault).

		VAULTS					
		HPTV	JTTV	JBTV	TSTV	AATV	DMTV
PRE-FLIGHT RESULTS	T1 Duration (s)	0.26	0.20	0.24	0.28	0.23	0.23
	VX1 Horizontal Velocity ($m.s^{-1}$)	3.92	4.07	3.70	3.54	3.86	3.99
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.17	3.00	3.39	3.54	3.11	3.17
	TH1 Take-off Angle (degrees)	74.5	85.1	78.9	82.3	76.2	76.0
	X1 Horizontal Displacement (m)	1.05	0.83	0.92	1.01	0.91	0.94
	Z1 Vertical Displacement (m)	0.54	0.39	0.57	0.58	0.53	0.50
	THDOT Angular Velocity (degrees. s^{-1})	239	219	253	249	269	231
	TH2 Contact Angle (degrees)	177.1	211.0	169.9	170.0	190.2	183.0
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	0.71	0.94	1.10	0.56	1.21	0.77

		VAULTS					
		HPTV	JTTV	JBTV	TSTV	AATV	DMTV
CONTACT VARIABLES	T2 Duration (s)	0.27	0.19	0.18	0.27	0.21	0.20
	X2 Horizontal Displacement (m)	0.73	0.56	0.56	0.76	0.62	0.64
	Z2 Vertical Displacement (m)	0.22	0.31	0.25	0.18	0.23	0.21
	FX1 Average Horizontal Compressive Force (N/body weight)	-1.39	-1.30	-1.09	-0.73	-1.36	-1.07
	FZ1 Average Vertical Compressive Force (N/body weight)	1.94	2.90	2.35	1.70	1.76	1.91
	FX2 Average Horizontal Repulsive Force (N/body weight)	-0.19	-0.17	-0.03	-0.10	-0.19	0.07
	FZ2 Average Vertical Repulsive Force (N/body weight)	0.80	0.81	0.82	0.74	0.74	0.95
	IX Horizontal Impulse (N.s/body mass)	-1.26	-1.22	-0.66	-0.63	-0.78	-0.57
	IZ Vertical Impulse (N.s/body mass)	2.49	2.27	2.16	2.34	1.66	2.26
POST-FLIGHT VARIABLES	XFL Horizontal Displacement (m)	1.13	1.50	1.70	1.19	1.59	1.61
	ZFL Vertical Displacement (m)	0.01	0.09	0.08	0.01	0.04	0.05
	VX3 Horizontal Velocity ($m.s^{-1}$)	2.76	3.05	3.26	3.03	3.28	3.41
	VZ3 Vertical Velocity ($m.s^{-1}$)	0.31	1.51	1.05	0.11	0.74	0.94
JUDGE'S SCORE		8.6	8.2	8.5	8.4	8.6	8.7

		VAULTS					
		HPH	JTH	JBH	TSH	AAH	DMH
PRE-FLIGHT RESULTS	T1 Duration (s)	0.36	0.31	0.23	0.25	0.33	0.29
	VX1 Horizontal Velocity ($m.s^{-1}$)	3.57	3.45	3.89	3.61	3.70	3.68
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.98	3.63	3.89	3.74	4.03	3.88
	TH1 Take-off Angle (degrees)	84.9	85.6	75.5	86.9	82.5	84.9
	X1 Horizontal Displacement (m)	1.32	1.10	0.87	0.94	1.25	1.08
	Z1 Vertical Displacement (m)	0.77	0.72	0.63	0.65	0.80	0.73
	THDOT Angular Velocity (degrees. s^{-1})	283	351	357	303	297	308
	TH2 Contact Angle (degrees)	154.1	151.9	168.4	169.7	140.0	148.0
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	0.20	0.76	1.46	1.22	0.75	0.94

		VAULTS					
		HPH	JTH	JBH	TSH	AAH	DMH
CONTACT VARIABLES	T2 Duration (s)	0.43	0.29	0.24	0.42	0.26	0.29
	X2 Horizontal Displacement (m)	0.96	0.69	0.66	1.12	0.72	0.81
	Z2 Vertical Displacement (m)	0.22	0.31	0.39	0.36	0.24	0.30
	FX1 Average Horizontal Compressive Force (N/body weight)	-1.24	-0.77	-1.17	-0.56	-0.99	-0.72
	FZ1 Average Vertical Compressive Force (N/body weight)	1.42	1.03	1.67	1.17	1.70	1.19
	FX2 Average Horizontal Repulsive Force (N/body weight)	-0.35	-0.27	-0.42	-0.18	-0.21	-0.32
	FZ2 Average Vertical Repulsive Force (N/body weight)	0.89	0.89	0.96	0.66	0.79	0.81
	IX Horizontal Impulse (N.s/body mass)	-2.02	-1.24	-1.52	-1.04	-1.22	-1.09
	IZ Vertical Impulse (N.s/body mass)	4.06	2.81	2.52	2.98	2.48	2.51
POST-FLIGHT VARIABLES	XFL Horizontal Displacement (m)	0.69	1.17	1.49	1.09	1.29	1.23
	ZFL Vertical Displacement (m)	-0.01	0.04	0.11	0.00	0.03	0.02
	VX3 Horizontal Velocity ($m.s^{-1}$)	1.78	2.24	2.50	2.58	2.62	2.55
	VZ3 Vertical Velocity ($m.s^{-1}$)	-0.16	0.76	1.28	0.08	0.56	0.56
JUDGE'S SCORE		8.0	9.0	8.8	7.8	8.8	8.9

		VAULTS					
		HPY	JTY	JBY	TSY	AAY	JBHSF
PRE-FLIGHT RESULTS	T1 Duration (s)	0.32	0.28	0.28	0.19	0.28	0.19
	VX1 Horizontal Velocity ($m.s^{-1}$)	3.05	3.91	3.78	3.66	3.56	4.11
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.96	3.74	4.00	3.61	3.89	3.83
	TH1 Take-off Angle (degrees)	86.3	78.7	75.2	83.2	87.9	79.3
	X1 Horizontal Displacement (m)	1.01	1.14	1.09	0.72	1.03	0.82
	Z1 Vertical Displacement (m)	0.74	0.66	0.71	0.52	0.74	0.60
	THDOT Angular Velocity (degrees. s^{-1})	295	339	296	323	329	352
	TH2 Contact Angle (degrees)	142.7	151.1	131.1	194.1	155.7	137.0
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	0.79	0.92	1.07	1.84	1.23	1.95

		VAULTS					
		HPY	JTY	JBY	TSY	AAY	JBHSF
CONTACT VARIABLES	T2 Duration (s)	0.20	0.23	0.24	0.30	0.26	0.20
	X2 Horizontal Displacement (m)	0.48	0.72	0.61	0.90	0.77	0.61
	Z2 Vertical Displacement (m)	0.25	0.38	0.32	0.40	0.33	0.43
	FX1 Average Horizontal Compressive Force (N/body weight)	-1.13	-0.90	-1.20	-0.62	-0.69	-1.18
	FZ1 Average Vertical Compressive Force (N/body weight)	1.16	0.88	1.82	1.20	1.81	1.62
	FX2 Average Horizontal Repulsive Force (N/body weight)	-0.15	-0.15	-0.33	-0.19	-0.19	-0.35
	FZ2 Average Vertical Repulsive Force (N/body weight)	1.04	1.22	0.96	0.98	0.96	0.93
	IX Horizontal Impulse (N.s/body mass)	-0.95	-1.15	-1.31	-0.63	-0.81	-1.38
	IZ Vertical Impulse (N.s/body mass)	2.54	2.94	2.72	1.96	2.49	2.41
POST-FLIGHT VARIABLES	XFL Horizontal Displacement (m)	1.26	1.64	1.68	1.41	1.63	1.98
	ZFL Vertical Displacement (m)	0.08	0.12	0.13	0.04	0.08	0.23
	VX3 Horizontal Velocity ($m.s^{-1}$)	2.23	2.80	2.52	3.02	2.84	2.72
	VZ3 Vertical Velocity ($m.s^{-1}$)	1.16	1.52	1.59	0.70	1.07	2.11
JUDGE'S SCORE		8.6	8.9	8.2	7.6	8.4	8.9

		VAULTS						
		BSTV	SCH	AGY	JTHH	JTHL	JTTVH	JTTVL
PRE-FLIGHT VARIABLES	T1 Duration (s)	0.26	0.26	0.19	0.25	0.19	0.17	0.13
	VX1 Horizontal Velocity ($m.s^{-1}$)	4.49	3.98	4.11	4.23	4.72	4.19	3.97
	VZ1 Vertical Take-off Velocity ($m.s^{-1}$)	3.01	3.88	3.71	3.70	3.43	3.45	2.93
	TH1 Take-off Angle (degrees)	50.8	80.4	57.5	76.5	68.3	79.5	75.8
	X1 Horizontal Displacement (m)	1.14	1.07	0.79	1.17	0.95	0.74	0.54
	Z1 Vertical Displacement (m)	0.49	0.65	0.53	0.65	0.51	0.38	0.28
	THDOT Angular Velocity (degrees. s^{-1})	238	333	360	345	309	238	208
	TH2 Contact Angle (degrees)	175.9	127.5	143.0	138.6	142.0	206.6	221.2
	VZ2 Contact Vertical Velocity ($m.s^{-1}$)	0.74	1.15	1.88	1.26	1.73	1.60	1.67

		VAULTS						
		BSTV	SCH	AGY	JTHH	JTHL	JTTVH	JTTVL
CONTACT VARIABLES	T2 Duration (s)	0.20	0.22	0.24	0.23	0.30	0.19	0.20
	X2 Horizontal Displacement (m)	0.71	0.71	0.65	0.76	1.05	0.63	0.63
	Z2 Vertical Displacement (m)	0.21	0.32	0.56	0.36	0.48	0.34	0.34
POST-FLIGHT VARIABLES	XFL Horizontal Displacement (m)	1.71	1.63	1.48	1.66	1.81	1.58	1.59
	ZFL Vertical Displacement (m)	0.07	0.09	0.22	0.09	0.10	0.16	0.14
	VX3 Horizontal Velocity ($m.s^{-1}$)	3.69	2.83	2.07	2.86	3.02	3.05	2.94
	VZ3 Vertical Velocity ($m.s^{-1}$)	0.81	1.67	1.91	1.22	1.22	1.64	1.55
JUDGE'S SCORE		8.7	8.8	8.6	9.1	8.7	8.6	8.1

APPENDIX E

Computer programs.

1. Centre of gravity program.

2. Graph plotting program.

```
C     PROGRAM TO CALCULATE THE CENTRE OF GRAVITY OF THE BODY GIVEN THE
C     COORDINATES OF CERTAIN LANDMARKS.
C
C     J(1 TO 11) REPRESENT THE HEAD,C7,SHOULDER,L1,HIP,KNEE,ANKLE, FOOT
C     ELBOW WRIST AND HAND RESPECTIVELY.
C
C      ***************;*****************************************************
C
C      SECTION TO READ DATA FROM FILES.
C
C      *********************************************************************
       DIMENSION XJ(11),YJ(11),XCSEG(9),YCSEG(9),XM(9),YM(9),WT(9),
     1 MXJ(11),MYJ(11),T(100)
       ICOUNT = 0
       K = 0
       L = 0
       DO 25 I = 1,9
       READ(7,26) WT(I)
26     FORMAT(F5.3)
25     CONTINUE
1000   DO 300 J = 1,11
       READ(5,*) MXJ(J),MYJ(J)
       IF (MXJ(J).EQ.9999) GO TO 800
       ICOUNT = ICOUNT + 1
       XJ(J) = FLOAT(MXJ(J))
       YJ(J) = FLOAT(MYJ(J))
300    CONTINUE
       L = L + 1
       READ(6,27) T(L)
27     FORMAT(F5.3)
C
C      *********************************************************************
C
C      CALCULATE THE CENTRES OF GRAVITY OF THE SEGMENTS.
C
C      *********************************************************************
```

COFG

```
      XCSEG(1) =XJ(1) - ((XJ(1) - XJ(2))*.433)
      YCSEG(1) = YJ(1) - ((YJ(1) - YJ(2))*.433)
      XCSEG(2) = XJ(2)  - ((XJ(2) - XJ(4))*.627)
      YCSEG(2) = YJ(2) - ((YJ(2) - YJ(4))*.627)
      XCSEG(3) = XJ(4) -((XJ(4) - XJ(5))*.599)
      YCSEG(3) = YJ(4) - ((YJ(4) - YJ(5))*.599)
      XCSEG(4) = XJ(5) -((XJ(5) -XJ(6))*.445)
      YCSEG(4) = YJ(5)  -((YJ(5) - YJ(6))*.445)
      XCSEG(5) = XJ(6) - ((XJ(6) -XJ(7))*.458)
      YCSEG(5) = YJ(6) - ((YJ(6) -YJ(7))*.458)
      XCSEG(6) = XJ(7) - ((XJ(7) - XJ(8))*.468)
      YCSEG(6) = YJ(7) - ((YJ(7) - YJ(8))*.468)
      XCSEG(7) = XJ(3) -((XJ(3) - XJ(9))*.476)
      YCSEG(7) = YJ(3) -((YJ(3)- YJ(9))*.476)
      XCSEG(8) = XJ(9) -((XJ(9) -XJ(10))*.484)
      YCSEG(8) = YJ(9) -((YJ(9) -YJ(10))*.484)
      XCSEG(9) = XJ(10) -((XJ(10) - XJ(11))*.493)
      YCSEG(9) = YJ(10) - ((YJ(10) - YJ(11))*.493)
C
C     *********************************************************************
C
C     CALCULATE THE MOMENTS ABOUT THE Y AXIS
C     *********************************************************************
      DO 900 J = 1,9
      XM(J) = XCSEG(J)*WT(J)
C     *******************************************************************
C
C     CALCULATE MOMENTS ABOUT THE X AXIS
C
C     ********************************************************************
C
      YM(J) = YCSEG(J)*WT(J)
C
C     ********************************************************************
C
C     CALCULATE THE  COORDINATES OF THE CENTRE OF GRAVITY OF THE WHOLE BODY
C
C     *******************************************************************
C
      XCOFG = XM(J) + XCOFG
      YCOFG = YM(J) + YCOFG
```

```
C
900   CONTINUE
C     ***************************************************************
C
C     OUTPUT RESULTS TO FILES AND PRINTER
C
C     ***************************************************************
      XCOFG = XCOFG/500.
      YCOFG = YCOFG/500.
      K = K+ 1
      WRITE (1,5) XCOFG,YCOFG,T(K)
5     FORMAT(8X,3(F10.3))
      WRITE(8,5) XCOFG,YCOFG
      WRITE(9,6) T(K),XCOFG
6     FORMAT(F7.3,F10.3)
      WRITE(10,6) T(K),YCOFG
600   CONTINUE
C
C     ***************************************************************
C
C     RE-ZERO
C
C     ***************************************************************
C
      XCOFG = 0
      YCOFG = 0
      DO 99 J =1,9
      XCSEG(J) =0
      YCSEG(J) =0
99    CONTINUE
      GO TO 1000
800   CONTINUE
      COUNT=FLOAT(ICOUNT/11.)

      WRITE(1,15) COUNT
15    FORMAT('COUNT EQUALS',2X,F6.2)
      CALL EXIT
      END
C
```

```
      LOGICAL PEN1
      DIMENSION X(11),Y(11)
      CALL S 5660
      CALL PAPENQ(XP,YP,1)
      XMIN=AMIN1(XP,YP)
      CALL WINDO2(0.0,XMIN,0.0,XMIN)
      CALL AXIPLO(0,0.0,0.0,3,3,8,8,0.0,5000.,0.0,5000.,DUM,0,DUM,0)
      PEN1=.TRUE.
      CALL APPARA
      CALL COFG
      DO 10 I=1,3000
      READ(6,*,END=20)(X(J),Y(J),J=1,11)
      IF ((I+3).LT.0)GO TO 10
      IF ((I-1)/7*7.NE.I-1)GO TO 10
      DO 8 J=1,11
      X(J)=X(J)*2
      Y(J)=Y(J)*2
8     CONTINUE
      IF(PEN1)II=1
      IF(.NOT.PEN1)II=2
      PEN1=.NOT.PEN1
      CALL PENSEL(II,0.0,0)
      CALL MAN(X,Y)
10    CONTINUE
20    CALL CHAMOD
      CALL TNOU('RUN COMPLETE',12)
      READ(1,*) JUNK
      CALL DEVEND
      STOP
      END
      SUBROUTINE MAN(X,Y)
      DIMENSION X(11),Y(11)
      CALL TNOU('IN MAN',6)
      CALL GRAMOV(X(1),Y(1))
      CALL GRALIN(X(2),Y(2))
      CALL GRALIN(X(4),Y(4))
      CALL GRALIN(X(5),Y(5))
      CALL GRALIN(X(6),Y(6))
      CALL GRALIN(X(7),Y(7))
      CALL GRALIN(X(8),Y(8))
      CALL GRAMOV(X(2),Y(2))
      CALL GRALIN(X(9),Y(9))
```

```
      CALL GRALIN(X(10),Y(10))
      CALL GRALIN(X(11),Y(11))
      RETURN
      END
      SUBROUTINE COFG
      DIMENSION X(100),Y(100)
      READ(7,*)(X(1),Y(1))
      X(1)=X(1)*1000
      Y(1)=Y(1)*1000
      CALL GRAMOV(X(1),Y(1))
      DO 30 I=2 , 99
      READ(7,*,END=30)(X(I),Y(I))
      X(I)=X(I)*1000
      Y(I)=Y(I)*1000
      CALL GRALIN(X(I),Y(I))
30    CONTINUE
      RETURN
      END
      SUBROUTINE APPARA
      WRITE(1,33)
33    FORMAT('INPUT THE COORDIATES OF THE FRONT ,TOP,MIDDLE POINT OF ')
      WRITE(1,35)
35    FORMAT('THE REUTHER BOARD')
      READ (1,*) A1,B1
      WRITE(1,36)
36    FORMAT('INPUT THE COODINATES OF THE TOPAND MIDDLE OF THE ')
      WRITE(1,38)
38    FORMAT('HORSE')
      READ(1,*) A2,B2
      CALL GRAMOV(0.,0.)
      CALL GRALIN(A1*2,B1*2)
      CALL GRAMOV((A2*2)-100,0.)
      CALL GRALIN((A2*2.)-100.,(B2*2*.6))
      CALL GRAMOV((A2*2)+100.,0.)
      CALL GRALIN((A2*2)+100.,(B2*2*.6))
      CALL GRAMOV((A2*2)-300.,(B2*2*.6))
      CALL GRALIN((A2*2)-300.,B2*2)
      CALL GRALIN((A2*2)+300.,B2*2)
      CALL GRALIN((A2*2)+300.,(B2*2)*.6)
      CALL GRALIN((A2*2)-300.,(B2*2)*.6)
      RETURN
      END
```

APPENDIX F

Details of subjects

Initials	Level	Age (years)	Weight (kg)	Height (cm)
HP	National	14	37.5	148.0
JT	National	17	59.2	167.7
JB	International	17	51.7	151.3
TS	Regional	16	54.2	165.8
AA	National	17	50.0	155.7
DM	International	19	59.5	164.1
BS	International	17	55.6	161.1
SG	International	21	45.5	157.5
AG	Regional	16	47.0	154.1

APPENDIX G

Correlation Matrices.

1. Layout squat vault.
2. Handspring vault.
3. Yamashita vault.

	T1	VX1	VZ1	VZ2	TH1	THDOT	TH2	X1	Z1	X2	Z2
VX1	-0.7895	1.0000									
VZ1	0.8130	-0.9518	1.0000								
VZ2	-0.6793	0.3781	-0.5281	1.0000							
TH1	-0.2533	-0.1071	0.0955	-0.1887	1.0000						
THDOT	0.4041	-0.6002	0.3914	0.3192	-0.4027	1.0000					
TH2	-0.8536	0.7769	-0.8488	0.3770	0.4245	-0.4907	1.0000				
X1	0.9035	-0.4649	0.5289	-0.6357	-0.5266	0.2384	-0.7600	1.0000			
Z1	0.8502	-0.8285	0.8078	-0.2418	-0.4629	0.7243	-0.9518	0.7220	1.0000		
X2	0.8604	-0.4435	0.4766	-0.8206	-0.2462	0.1281	-0.5251	0.8892	0.5234	1.0000	
Z2	-0.8550	0.6176	-0.6613	0.5862	0.4719	-0.4501	0.7800	-0.8070	-0.7980	-0.8064	1.0000
T2	0.8162	-0.3960	0.3887	-0.7558	-0.1831	0.1137	-0.4285	0.8602	0.4485	0.9665	-0.6573
FX1	0.5620	-0.7384	0.8474	-0.6557	0.3672	0.0581	-0.5430	0.2549	0.4546	0.3846	-0.5616
FZ1	-0.7303	0.4957	-0.4566	0.3488	0.6137	-0.6235	0.6442	-0.7223	-0.7512	-0.7251	0.9398
FX2	0.0138	-0.0910	0.3209	-0.1416	-0.1336	-0.1776	-0.3668	-0.0212	0.1791	-0.1415	-0.2884
FZ2	-0.3489	0.5100	-0.2559	0.0035	-0.2591	-0.5585	0.0558	-0.1368	-0.2783	-0.2682	0.0589
IX	0.2808	-0.5549	0.6012	-0.0630	-0.1174	0.4513	-0.5343	0.0431	0.5427	0.0201	-0.5636
IZ	0.3414	0.0044	0.2294	-0.7265	0.1561	-0.6849	-0.2224	0.4605	-0.0359	0.4282	-0.0992
XFL	-0.6682	0.2399	-0.2529	0.7674	-0.0014	0.1313	0.2385	-0.7395	-0.2172	-0.8708	0.4200
ZFL	-0.8355	0.4144	-0.3936	0.6307	0.4492	-0.3335	0.5399	-0.8973	-0.6010	-0.9596	0.8389
VX3	-0.3895	0.0383	-0.0191	0.4472	-0.0884	0.2264	0.0339	-0.5076	-0.0072	-0.5333	-0.0143
VZ3	-0.9466	0.6343	-0.6112	0.6378	0.3761	-0.4435	0.7081	-0.9208	-0.7633	-0.9377	0.8780
Z	-0.7964	0.3465	-0.3424	0.7404	0.2372	-0.1071	0.4122	-0.8668	-0.4333	-0.9694	0.6667

	T2	FX1	FZ1	FX2	FZ2	IX	IZ	XFL	ZFL	VX3	VZ3
T2	1.0000										
FX1	0.2328	1.0000									
FZ1	-0.6009	-0.3146	1.0000								
FX2	-0.3675	0.5267	-0.1083	1.0000							
FZ2	-0.4224	-0.0052	0.1670	0.7865	1.0000						
IX	-0.2000	0.6926	-0.4965	0.7286	0.2105	1.0000					
IZ	0.4425	0.2661	0.1782	0.1674	0.3022	-0.3259	1.0000				
XFL	-0.9527	-0.1403	0.3332	0.4632	0.4008	0.4333	-0.5984	1.0000			
ZFL	-0.9302	-0.2236	0.8441	0.2123	0.3224	-0.0435	-0.2130	0.7827	1.0000		
VX3	-0.7172	0.1985	-0.0686	0.6732	0.4544	0.7624	-0.5921	0.8661	0.4574	1.0000	
VZ3	-0.9061	-0.3788	0.8402	0.1528	0.4048	-0.1677	-0.2183	0.7427	0.9631	0.4315	1.0000
Z	-0.9972	-0.1927	0.6235	0.3578	0.3830	0.2064	-0.4297	0.9441	0.9441	0.7009	0.9034

Layout squat vault.

	T1	VXL	VZ1	VZ2	TH1	THDOT	TH2	X1	z1	X2	Z 2
T1	1.0000										
VX1	-0.5652	1.0000									
VZ1	0.3733	0.5207	1.0000								
VZ2	-0.9753	0.6197	-0.3014	1.0000							
TH1	0.4445	-0.8538	-0.3591	-0.4981	1.0000						
THDOT	-0.5841	0.2151	-0.5564	0.5997	-0.5399	1.0000					
TH2	-0.7467	0.2743	-0.3950	0.6013	-0.2481	0.3509	1.0000				
X1	0.9888	-0.4661	0.4927	-0.9498	0.3991	-0.6598	-0.7668	1.0000			
Z1	0.9265	-0.3784	0.5141	-0.8293	0.3546	-0.6001	-0.9179	0.9528	1.0000		
X2	0.0136	-0.3079	-0.0835	-0.1488	0.6243	-0.6483	0.3908	0.0326	-0.1270	1.0000	
Z2	-0.9742	0.4232	-0.5388	0.9292	-0.4012	0.7041	0.7865	-0.9958	-0.9634	-0.0511	1.0000
T2	0.2708	-0.4920	-0.0826	-0.4332	0.6431	-0.6324	0.3123	0.2566	0.0232	0.9225	-0.2481
FX1	-0.3342	-0.3846	-0.6537	0.3374	0.6233	0.0141	0.0888	-0.3638	-0.2480	0.3649	0.3405
FZ1	0.0015	0.7531	0.8130	0.0978	-0.7504	-0.0819	-0.0976	0.1112	0.1512	-0.3495	-0.1312
FX2	0.1299	-0.4784	-0.2371	-0.0599	0.6757	-0.3939	-0.2140	0.1499	0.2377	0.4354	-0.1645
FZ2	0.1054	0.2404	0.1344	-0.1164	-0.6457	0.5399	-0.0432	0.0555	-0.0038	-0.7118	-0.0106
IX	-0.4061	-0.0174	-0.3697	0.5309	0.2156	0.1622	-0.1058	-0.3844	-0.1476	-0.0455	0.3521
IZ	0.5568	-0.4517	0.1317	-0.7126	0.3703	-0.5118	0.1236	0.5240	0.2442	0.5600	-0.4899
XFL	-0.6817	0.6401	-0.0846	0.8137	-0.6450	0.6742	0.0864	-0.6496	-0.4206	-0.6434	0.6293
ZFL	-0.5999	0.6769	-0.0403	0.6626	-0.8999	0.8389	0.2828	-0.6006	-0.5077	-0.7475	0.6168
VX3	-0.6384	0.4782	-0.0664	0.7705	-0.2133	0.2314	0.0391	-0.5702	-0.3176	-0.1744	0.5174
VZ3	-0.5549	0.5581	-0.1410	0.6518	-0.7648	0.8651	0.0917	-0.5662	-0.4044	-0.8391	0.5756
Z	-0.6716	0.6902	-0.0654	0.7737	-0.8096	0.7930	0.1935	-0.6552	-0.4865	-0.7289	0.6531

	T2	FX1	FZ1	FX2	FZ2	IX	IZ	XFL	ZFL	VX3	V Z3
T2	1.0000										
FX1	0.1300	1.0000									
FZ1	-0.3713	-0.7273	1.0000								
FX2	0.2792	0.6867	-0.3120	1.0000							
FZ2	-0.4551	-0.7479	0.3155	-0.8624	1.0000						
IX	-0.3440	0.7991	-0.2383	0.7026	-0.6321	1.0000					
IZ	0.8253	-0.3799	-0.1303	-0.1294	0.0817	-0.7739	1.0000				
XFL	-0.8670	0.1368	0.3125	-0.1160	0.1472	0.5749	-0.9389	1.0000			
ZFL	-0.7876	-0.3251	0.4452	-0.5637	0.6208	0.0481	-0.5901	0.8205	1.0000		
VX3	-0.5338	0.5313	0.1381	0.3707	-0.4481	0.8679	-0.9012	0.8108	0.3566	1.0000	
VZ3	-0.9089	-0.1304	0.2905	-0.4365	0.5436	0.2489	-0.7578	0.9003	0.9525	0.4800	1.0000
Z	-0.8671	-0.0986	0.3971	-0.3562	0.4025	0.3265	-0.8013	0.9541	0.9541	0.6118	0.9710

Handspring vault.

	T1	VX1	VZ1	VZ2	TH1	THDOT	TH2	X1	Z1	X2	Z2
T1	1.0000										
VX1	-0.4390	1.0000									
VZ1	0.8189	-0.3919	1.0000								
VZ2	-0.9621	0.2801	-0.7066	1.0000							
TH1	0.0760	-0.6835	-0.0650	0.1191	1.0000						
THDOT	-0.3795	0.5701	-0.6943	0.2976	0.1292	1.0000					
TH2	-0.8789	0.1136	-0.8977	0.8799	0.3453	0.4900	1.0000				
X1	0.8124	0.1667	0.6354	-0.8725	-0.3436	-0.0273	-0.8824	1.0000			
Z1	0.9340	-0.3786	0.8998	-0.8256	0.1490	-0.3609	-0.8659	0.7805	1.0000		
X2	-0.8826	0.5701	-0.8238	0.8653	0.0767	0.7239	0.8328	-0.5887	-0.7528	1.0000	
Z2	-0.8189	0.8035	-0.8494	0.6866	-0.2949	0.7517	0.6754	-0.3715	-0.7936	0.8999	1.0000
T2	-0.9402	0.4473	-0.6882	0.9722	0.0551	0.4318	0.8178	-0.7379	-0.7615	0.9335	0.7722
FX1	-0.7047	0.2371	-0.7747	0.7540	0.4849	0.7574	0.8604	-0.6023	-0.5826	0.9022	0.6838
FZ1	0.0879	0.0305	0.5739	0.1013	0.0046	-0.3380	-0.3142	0.1112	0.4154	-0.0269	-0.2455
FX2	0.0702	-0.3596	-0.4477	-0.0921	0.6421	0.4905	0.3808	-0.1382	-0.1082	0.0920	0.0322
FZ2	0.2368	0.2798	-0.2938	-0.4552	-0.2510	0.4897	-0.1139	0.4486	-0.0355	-0.0991	0.2264
IX	-0.5773	-0.3209	-0.5964	0.7014	0.7643	0.3125	0.8581	-0.8291	-0.5065	0.5931	0.2633
IZ	0.7398	0.2561	0.5061	-0.8549	-0.4577	0.0314	-0.8238	0.9773	0.6476	-0.5504	-0.2590
XFL	-0.0086	0.8270	0.1120	-0.0482	-0.5453	0.3923	-0.3077	0.5283	0.1664	0.2676	0.4088
ZFL	0.5928	0.4075	0.5638	-0.7085	-0.6999	-0.1323	-0.8481	0.9069	0.5572	-0.5000	-0.1894
VX3	-0.8163	0.6602	-0.8046	0.7782	0.0163	0.8050	0.7560	-0.4563	-0.6920	0.9873	0.9281
VZ3	0.6316	0.3497	0.5713	-0.7550	-0.6886	-0.1669	-0.8633	0.9117	0.5658	-0.5588	-0.2355
Z	0.3216	0.6797	0.3721	-0.4166	-0.6856	0.1431	-0.6363	0.7901	0.3984	-0.1279	0.1208

	T2	FX1	FZ1	FX2	FZ2	IX	IZ	XFL	ZFL	VX3	VZ3
T2	1.0000										
FX1	0.7958	1.0000									
FZ1	0.1883	-0.0963	1.0000								
FX2	-0.1486	0.4225	-0.7253	1.0000							
FZ2	-0.4132	-0.0875	-0.8038	0.5477	1.0000						
IX	0.6153	0.8164	-0.1245	0.5152	-0.3241	1.0000					
IZ	-0.7297	-0.6060	-0.0623	-0.0905	0.5984	-0.8631	1.0000				
XFL	0.1736	0.0228	0.4411	-0.5147	0.0846	-0.5171	0.5117	1.0000			
ZFL	-0.5786	-0.6949	0.1564	-0.4480	0.3779	-0.9741	0.9270	0.6496	1.0000		
VX3	0.8766	0.8792	-0.0455	0.1013	0.0094	0.4950	-0.4119	0.3824	-0.3784	1.0000	
VZ3	-0.6412	-0.7382	0.0899	-0.3995	0.4217	-0.9813	0.9400	0.5783	0.9955	-0.4396	1.0000
Z	-0.2230	-0.3700	0.3290	-0.5300	0.2546	-0.8210	0.7921	0.9082	0.9082	0.0022	0.8665

Yamashito vault.