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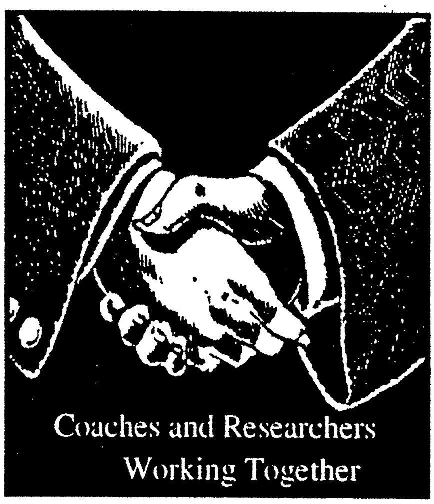
PROCEEDINGS



ABSTRACT: Using accelerometer and microcomputer technology, a system was developed to monitor vertical acceleration of the springboard tip in response to the actions of the diver during the hurdle and take-off of 3-m dives. The system was designed to be non-intrusive and was used to collect normative data on the hurdle and take-off patterns of competitors at the 1991 World Diving Cup and the 1992 Canadian Olympic Trials both of which were held at the Pan Am Pool in Winnipeg, Manitoba. Custom software was written to estimate hurdle support, hurdle flight and take-off durations. These values, when compared with the times obtained from video records of forward and reverse dives without limit performed by 12 competitors at the World Diving Cup, revealed that only hurdle flight duration could be estimated with acceptable accuracy from the accelerometer records. Analysis of the acceleration patterns, however, provided insights into the way in which divers 'caught the board' and into their relative consistency from one dive to another. It was concluded that the accelerometer based feedback system, supported by qualitative video records of the take-offs, could provide immediate and meaningful feedback on boardwork. Because of hardware requirements, the system would not be feasible for use by individual coaches and/or clubs, but could be employed during national team training camps or permanently installed at a national training center.

A Springboard Feedback System:
Considerations and Implications for Coaching

Ian C. Jones
Dept. of Physical Medicine and Rehabilitation
Victoria Hospital
800 Commissioners Road East
London, ON, CANADA. N0M 2A0
Phone: 519/685 8500 ext 3079

Marc A. Pizzimenti
Education Services
Parkwood Hospital
University of Western Ontario
London, ON, Canada. N6A 3K7

Doris I. Miller
Faculty of Kinesiology
University of Western Ontario
London, ON, Canada. N6A 3K7

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INTRODUCTION

Over the past two decades, a better understanding of the kinematics of springboard diving performance has been achieved. Most of the research has focused upon the diver's motion assessed from digitizing film, and more recently, video (e.g., Miller, 1984; Miller and Munro, 1984, 1985a,b; Sanders and Wilson, 1987, 1988). Attention has also been directed to evaluating the mechanical characteristics of the springboard (Lanoue, 1936; Darda, 1972; Torre, 1977a,b; Cromwell, 1984; Stone, 1987; Stilling, 1989; Sprigings et al., 1987, 1989, 1990; Kuipers and van de Ven, 1992; Boda, 1992). As yet, however, no comprehensive and systematic attempt has been made to link the two approaches. Part of the reason has been the lack of a functional system to monitor the response of the springboard to the actions of the diver under practice and competitive conditions. Such a system could provide performance information to complement the position and velocity data now readily obtainable with computerized video digitizing systems.

The potential value in being able to readily access the response of the springboard and to interpret this information relative to the diver's technique is evident. Therefore, the current project was designed: (1) to develop a springboard monitoring system capable of providing a consistent representation of springboard response to the actions of the diver during take-off; and (2) to provide a functional interpretation of the output, appropriately packaged for use by coaches and divers.

PROCEDURES

System Development

A primary concern in the development of a valid and reliable springboard response monitoring system was to select a transducer which could operate under both practice and competition conditions. It was important that the system itself and data collection procedures be non-invasive and invisible to the divers. The presence of the system could not adversely affect or be perceived to adversely affect performance. The mass and size of the transducer, therefore, had to be insignificant relative to those of the springboard and the diver. In addition, the transducer attachment on the board had to be virtually 'maintenance free' for several hours, and preferably for an entire day so that it could be used during competitions.

After considering several transducers and methods of attachment, it was decided to use a 12 gm Kistler Piezobeam accelerometer (model 8638B50) attached by a small threaded stud to a 2 gm mounting pad. The latter was securely fastened to the middle of the underside of the tip of the board using epoxy adhesive (3M 1838). A 20 m light-weight teflon coated and hermetically sealed coaxial cable (Kistler 1631C) conveyed the signal from the transducer, along the length of the torsion box on the underside of the board, to a microcomputer at poolside. The output, which represented acceleration normal to the surface of the diving board, approximated vertical acceleration of the board tip.

Data Collection

Following several pilot studies, normative data were collected at the 1991 World Diving Cup and the 1992 Canadian Olympic Trials, both of which were held at the Pan Am pool in Winnipeg, Manitoba. Both 3-m boards used in the competitions were instrumented. Data sampling was at a rate of 500 Hz and was initiated manually through a series of keystrokes on the microcomputer situated in the first row of the balcony adjacent to the boards.

At the World Diving Cup, the accelerometer output was low-pass filtered (Frequency Devices Lowpass Filter 901F1) with a frequency cut-off of 10 Hz and input to a 12 bit analog-to-digital (A/D) converter prior to processing with custom software in an Apple IIe microcomputer equipped with a dual floppy disk drive. This system permitted the collection of only 3 s of data per dive. Time required for data processing between trials limited the number of dives which could be sampled.

Output from the accelerometers at the Canadian Olympic Trials was collected with Codas software and a 12 bit A/D converter (Dataq Instruments, Inc.) installed in a Toshiba T3200SX. The computer and software change allowed a greater number of dives to be collected since the values could be stored directly on a hard disk. A greater amount of data per take-off was also available as data collection continued until it was manually terminated by a keystroke. Malfunction of the analog lowpass filter unit at the beginning of the competition necessitated subjecting the acceleration data to a fourth order Butterworth digital filter after collection. This software procedure was not an adequate substitute for the analog filter.

Data Analysis

Board tip acceleration records from the forward and reverse dives without limit for 8 women and 6 men who placed in the top 12 in their respective 3-m competitions at the World Diving Cup were subjected to analysis. In all but one instance, it was possible to obtain two different records of the same dive performed by a particular diver. In total, data from 26 forward and 24 reverse dives were examined.

Custom software was developed to analyze take-off acceleration files collected with the accelerometers. This software displayed individual acceleration patterns and, by movement of a cursor along the curve, allowed the operator to mark the beginning and the end of the hurdle and take-off support phases. The software also permitted integration of the curves to approximate velocity and vertical position of the board tip. In addition, the acceleration record from one dive could be superimposed on another to provide a visual indication of the consistency of the two performances.

Selected video records were chosen for analysis to serve as a logical check on the acceleration patterns obtained from the accelerometer. The board tip vertical position in these records was digitized frame by frame at a sampling rate of 60 Hz using a Peak 2D Motion Analysis System (Peak Performance Technologies Inc., Englewood, CO). These position values were smoothed with a fourth order Butterworth digital filter with the frequency cut-off determined by the procedure of Jackson (1979). They were then differentiated to determine velocity and acceleration. The accelerometer patterns of the hurdle and take-off were subsequently examined to identify points or patterns of functional significance for divers and their coaches.

RESULTS AND DISCUSSION

Interpretation of Board Tip Acceleration Curves

Although the data obtained from the accelerometers represented the acceleration of the springboard tip in a direction perpendicular to the diving surface, it was assumed that this acceleration could be interpreted as acting in the vertical direction. In the measurement convention adopted, positive signified upward acceleration and negative signified downward acceleration of the board tip.

For the purposes of analysis, the board tip vertical acceleration-time history was divided into five functionally significant phases: (1) hurdle preflight (2) hurdle support (3) hurdle flight (4) take-off support and (5) dive flight.

The two most definitive positive deflections in the accelerometer curves were associated with the major portion of the support phases of the hurdle and take-off, respectively. During both of these support phases, the board tip was depressed significantly and then recoiled. The period of depression just before the board's lowest point and the period of recoil which immediately follows were associated with increasing vertical velocity, and thus positive or upward acceleration (Fig. 1). These definitive positive acceleration portions of the curve, however, did not account for the entire period of board contact.

To locate the beginning and the end of the hurdle and take-off support periods, discontinuities in the established oscillation pattern introduced by the diver's contact with the board had to be identified. The location of initial contact in the hurdle was the most difficult to discern. By contrast, initial contact in the take-off could usually be identified with reasonable certainty. For the purpose of standardization, it was assumed that effective contact between the diver and the board in the take-off concluded when the positive acceleration deflection associated with that period returned to zero.

The three periods of flight could also be discerned in the accelerometer records. Prior to the hurdle, the acceleration curve remained near zero. There was a detectable difference in the configuration depending upon how vigorously the diver contacted the board to begin the hurdle. Some divers made a smooth transition with little or no noncontact following the last step, while others had longer preflights and greater preflight acceleration deflections.

During the hurdle flight, two major positive excursions could be discerned in the acceleration curve. These excursions represented the two downward oscillations of the board tip which occurred during hurdle flight (Fig. 1). Visual inspection of the video records showed that regions of more rapid and slower motion were superimposed on the two basic upward and downward motions of the board. Thus, it appeared that the diver excited at least two modes of board oscillation during hurdle support.

After the diver left the board for flight of the dive, the acceleration curve oscillated from negative to positive in a more rapid fashion as the board whipped and vibrated. When sampling was continued long enough, a regular damped oscillation pattern emerged as the board gradually lost energy and settled back on the fulcrum.

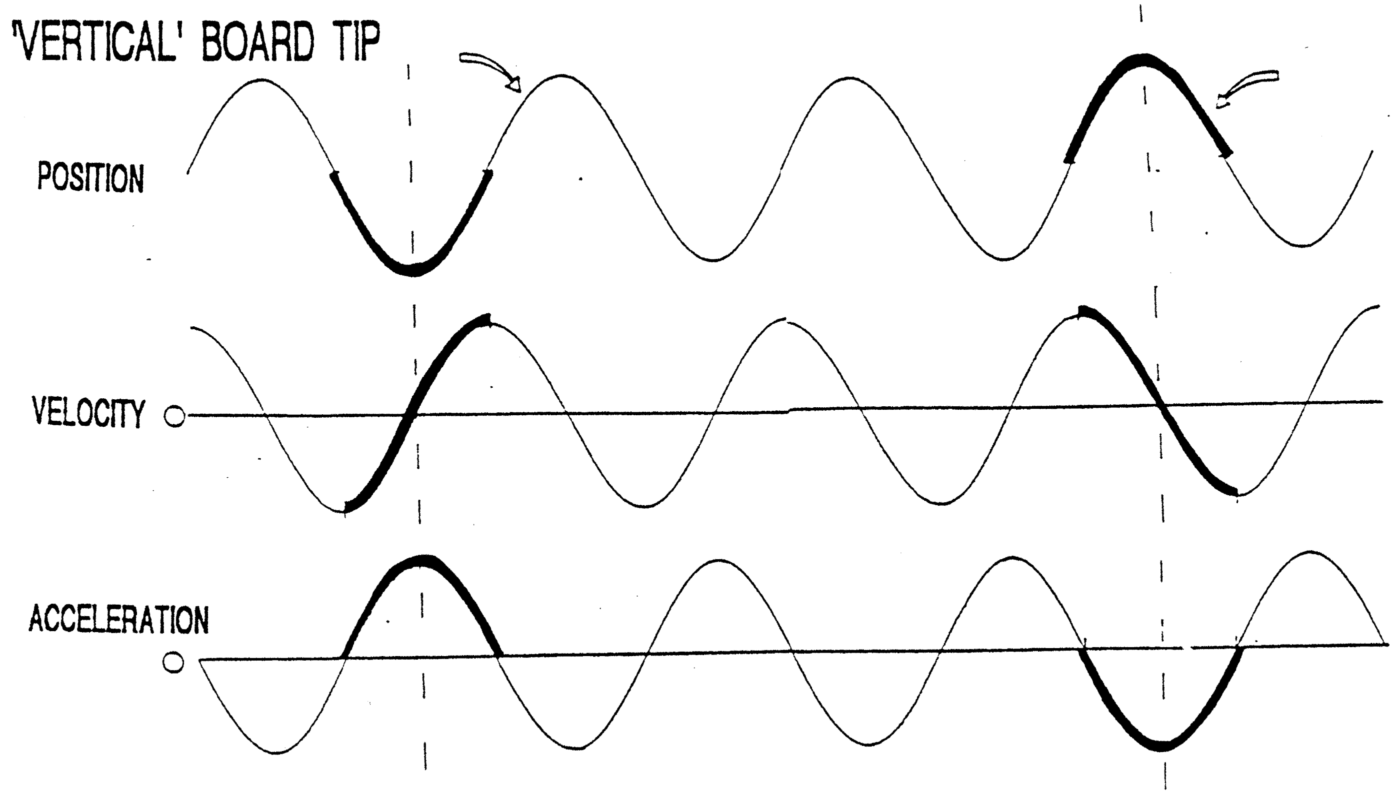


Figure 1. Theoretical vertical position, velocity and acceleration of the board tip assuming the board is moving up and down in a regular fashion. The first darkened region shows the end of board depression and beginning of recoil. The arrow indicates where the diver would likely lose contact with the board. The second darkened region shows the end of the upward motion of the board and the beginning of its downward motion as would occur as the diver approaches contact with the board. The arrow in this case shows that if the diver contacts the board when it has started its downward motion, the vertical velocity of the board will be negative and the acceleration, while negative, will be approaching the zero line.

The overall board tip vertical acceleration pattern was evident in the accelerometer record obtained from Mark Lenzi's 305B performance during the team competition at the World Diving Cup in 1991 (Fig. 2). Oscillations at the beginning of the record signified hurdle preflight. This was followed by hurdle support, shown in the blackened area between the curve and the zero line. The latter began and ended when the acceleration was negative, but the major portion of this phase was associated with positive or upward acceleration. The irregular, but predictable, oscillation of hurdle flight which followed was interrupted when Lenzi contacted the board for the take-off portion of the dive. This contact occurred as the negative acceleration neared the zero line, signifying maximum downward velocity of the board tip. The take-off (second blackened area) thus began when acceleration was negative but, like hurdle support (first blackened area), the major portion of this period

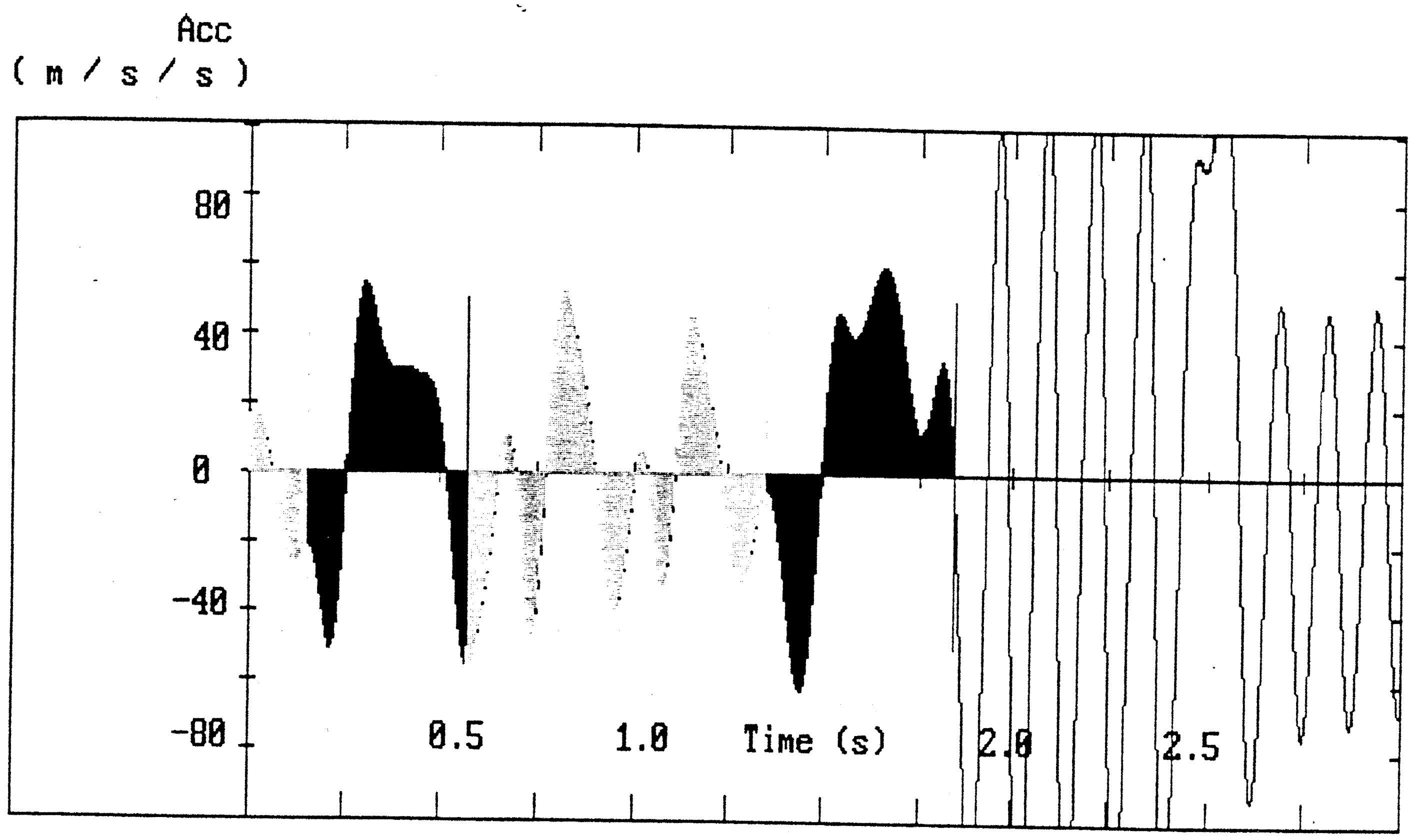


Figure 2. Board tip acceleration pattern from Mark Lenzi's 305B during the team competition at World Diving Cup VII. The black areas indicate board contact by Lenzi. He contacted the board after the hurdle very close to when the board reached maximum downward velocity. A pre-hurdle flight period is also indicated by the first positive light gray area.

was associated with positive or upward acceleration. A similar interpretation can be applied to Irina Lashko's 105B performances from the semi-final and final competitions (Fig. 3).

Comparison of Video and Accelerometer Patterns

Vertical acceleration magnitudes and overall configuration of the vertical board tip acceleration patterns calculated through double differentiation of video position data provided a logical check for the data obtained directly from the accelerometers (Fig. 4). Because of the slower sampling rate with the video (60 Hz compared with 500 Hz for the accelerometers), and because of the inherent error due to noise in attempting to calculate acceleration through the double differentiation of experimentally obtained position-time data from video, the acceleration patterns obtained from the accelerometers were considered more accurate. The identification of initial and final contacts between the diver and the board, however, could be located with greater certainty from

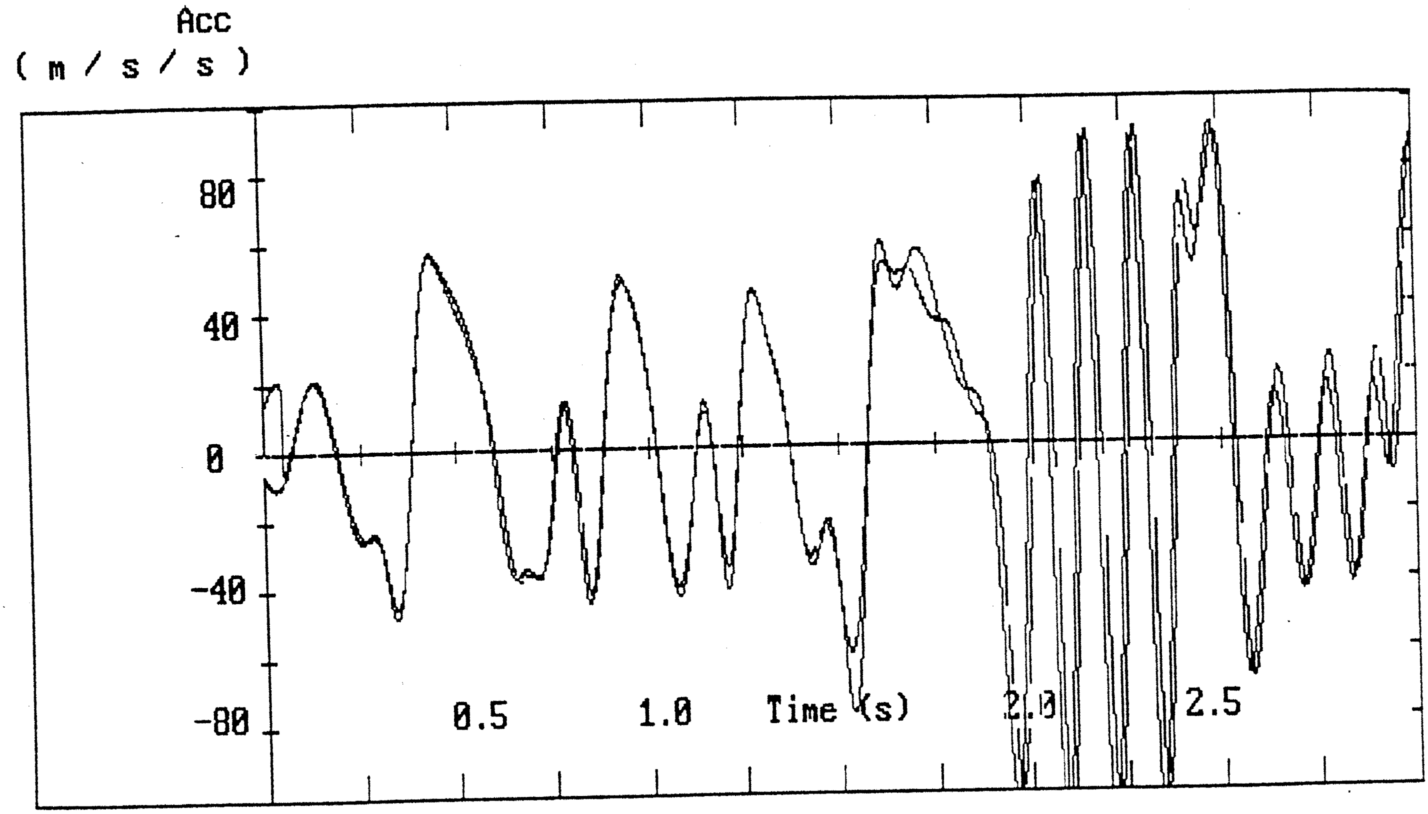


Figure 3. Irina Lashko's 105B board tip acceleration patterns from the semi-finals and finals at the World Diving Cup VII.

the video records and, consequently, they were considered the criterion when assessing the adequacy with which support and flight durations could be estimated (Table 1).

Although inter-rater reliability in estimating temporal components of the hurdle and take-off from the accelerometer records was acceptable (correlations ranging from r = 0.86 for hurdle support to r = 0.95 for the time to maximum springboard depression), the correlations between the raters and the video criteria were low, with the exception of the duration of hurdle flight. These low correlations reflected the difficulty in identifying the beginning of the hurdle support and the end of the take-off phases from the acceleration record.

Because the hurdle flight time could be assessed from the accelerometer records, it was employed to approximate the diver's vertical velocity on contact with the board at the beginning of the take-off under the assumption that the height of the diver's center of gravity (CG) was the same at the beginning and the end of hurdle flight. In reality, the diver's CG is slightly lower on landing. Consequently, the downward velocity values for the diver's CG at the end of hurdle flight would be slightly underestimated. This information, nevertheless, may be of interest from a coaching standpoint (Tables 2 and 3).

Although the correlations between take-off support times estimated from the accelerometer and video were low, it was believed that the region on the accelerometer record associated with this part of the performance could be identified reliably (inter-rater r= 0.94) and represented a functionally significant variable. Comparison of this duration

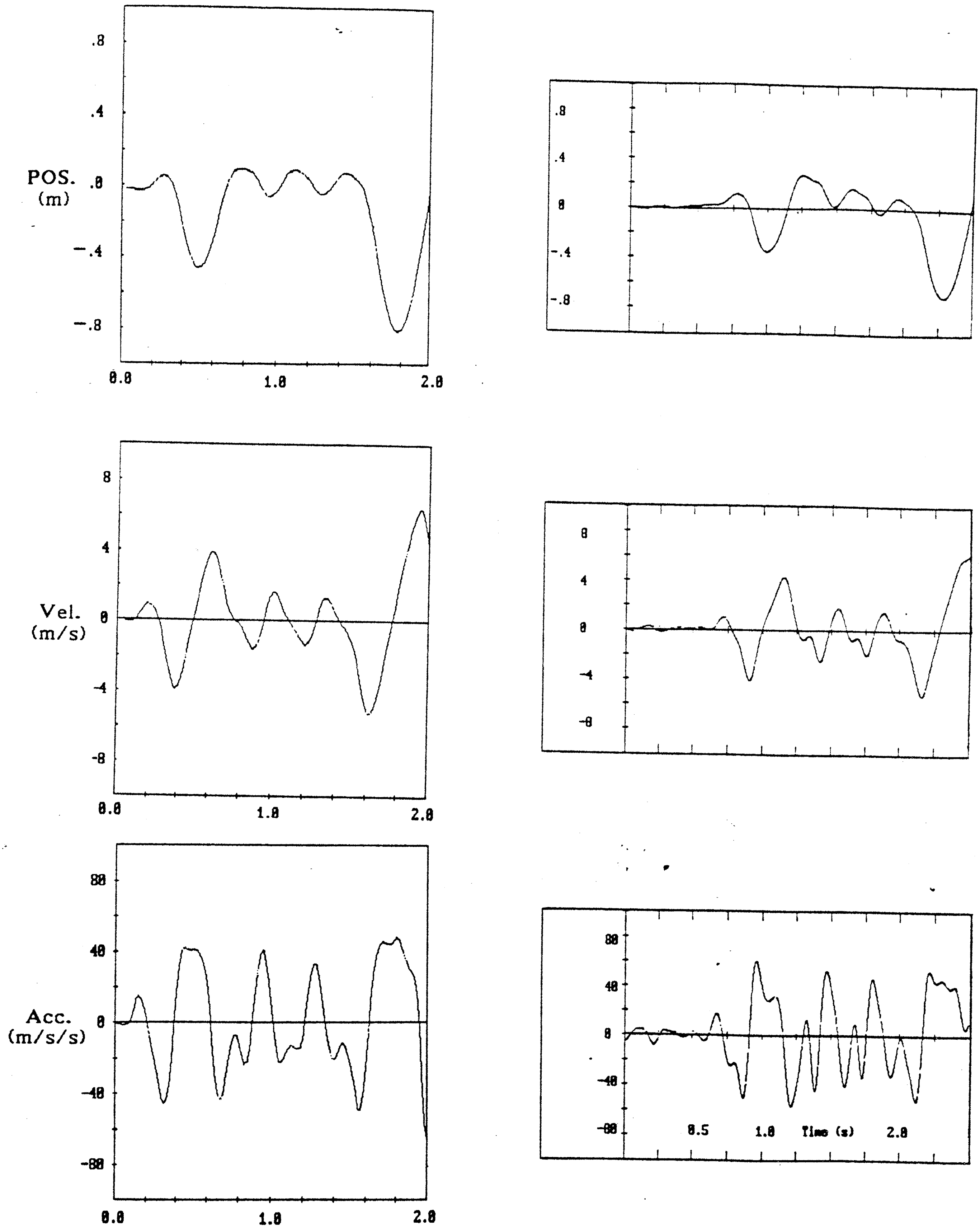


Figure 4. Board tip vertical position, velocity and acceleration of Mark Lenzi's 307C (semi-finals) obtained from video (left) and accelerometer (right).

Table 1. Correlations Between Raters and Between Raters and the Video Temporal Criterion Measures Based on 36 Observations (df 34).

	Inter-rater	Rater One	Rater Two
Hurdle Support Duration	0.86	0.64	0.76
Hurdle Flight Duration	0.92	0.85	0.93
Take-off Support Duration	0.94	0.47	0.48
Time to Maximum Depression	0.95	0.06	0.06

across dives of a given competitor may provide an indication of consistency of performance.

The virtual lack of correlation between the time to maximum depression of the board and the criterion was related to the fact that this calculation assumed that both the vertical board tip position and velocity were zero at the beginning of the integration interval. Under competitive conditions and the limited time for data sampling per dive at the World Diving Cup, it was unlikely that these assumptions were valid. Twofold differences in the magnitude of this estimate of a given dive of a particular competitor were not uncommon. Consequently, the only temporal parameter which could be estimated with acceptable accuracy from the accelerometer record was hurdle flight.

Functional Significance of the Patterns

Catching the Board. Examination of the acceleration pattern at the instant that the diver contacted the board in the take-off provided useful information on how the diver 'caught the board'. In almost all cases of the highly skilled divers analyzed, contact occurred when board tip vertical acceleration was negative. It also tended to take place during the latter half of what one would predict to be the negative acceleration deflection.

Reference to Figure 1 may help to place this negative acceleration into the context of vertical motion of the tip of the springboard. Upward motion of the springboard is associated with positive velocity, while downward motion is associated with negative velocity. Increasing velocity (i.e., a positive slope of the velocity-time curve) is associated with positive acceleration whereas negative slope on the velocity-time curve signifies negative downward acceleration.

At the beginning of the period of negative acceleration before the diver contacts the board, the board would be moving upward but slowing its rate of upward motion (i.e., negative acceleration). Towards the latter half of the negative acceleration, the board, having reached its highest point, would be moving downward and increasing its rate of downward motion (i.e., also negative acceleration). Both of these conditions represent a decrease in vertical velocity and thus a negative or downward slope in the velocity-time curve.

The later the diver 'catches the board' during this negative acceleration period, the faster the board will be moving downward. Theoretically, the board would have its greatest downward velocity when the vertical acceleration is zero. Consequently, it was not surprising that highly skilled divers such as Mark Lenzi, Mark Bradshaw, Tan Liangd, Sergey Lomanovskiy, Fernando Platas, Irina Lashko and Britta Baldus consistently 'caught the board' after its negative vertical acceleration had turned back toward the zero line. Contacting the springboard when its downward velocity is near maximum should result in greater maximum depression as

Table 2. Characteristics of Selected Dives from the Forward Group at the World Diving Cup 1991.

Diver	Dive	Round	Score	Fulcrum Setting	Hurdle Flight Time (s)	Estimated Vertical Velocity (m/s)	Take-off Support Time (s)
Lenzi	107B	T	7.4	8.00	0.78	-3.9	0.46
Lenzi	107B	S	7.9	8.00	0.79	-3.9	0.47
Liangd	107B	T	7.6	6.00	0.81	-4.0	0.40
Liangd	107B	S	8.1	5.75	0.84	-4.2	0.41
Lomanovskiy	107B	T	6.2	7.25	0.80	-4.0	0.45
Lomanovskiy	107B	S	8.0	7.25	0.80	-4.0	0.43
Platas	107B	T	7.5	8.00	0.76	-3.8	0.41
Platas	107B	S	7.0	8.00	0.77	-3.8	0.41
Lepoole	107B	T	7.3	7.25	0.79	-3.9	0.47
Lepoole	107B	Q	7.2	——	0.80	-4.0	0.45
Lepoole	107B	S	7.1	6.25	0.81	-4.0	0.47
Lucero	105B	T	7.3	5.75	0.70	-3.5	0.41
Lucero	105B	Q	6.0	5.75	0.70	-3.5	0.39
Lucero	105B	S	7.4	5.50	0.70	-3.5	0.39
Lashko	105B	S	7.4	9.00	0.79	-3.9	0.42
Lashko	105B	F	7.7	9.00	0.77	-3.8	0.43
Depiero	105B	T	7.4	5.25	0.76	-3.8	0.36
Depiero	105B	Q	7.1	5.00	0.70	-3.5	0.41
Bartova	105B	S	7.2	3.50	0.66	-3.3	0.40
Bartova	105B	F	7.5	3.50	0.68	-3.4	0.39
Pelletier	105B	T	7.0	7.50	0.69	-3.4	0.44
Pelletier	105B	S	7.6	7.50	0.71	-3.5	0.41
Haisong	105B	T	6.4	8.00	0.70	-3.5	0.41
Haisong	105B	S	8.1	8.00	0.70	-3.5	0.41
Lindner	105B	S	7.0	7.50	0.69	-3.4	0.45
Lindner	105B	F	6.8	7.50	0.71	-3.5	0.43

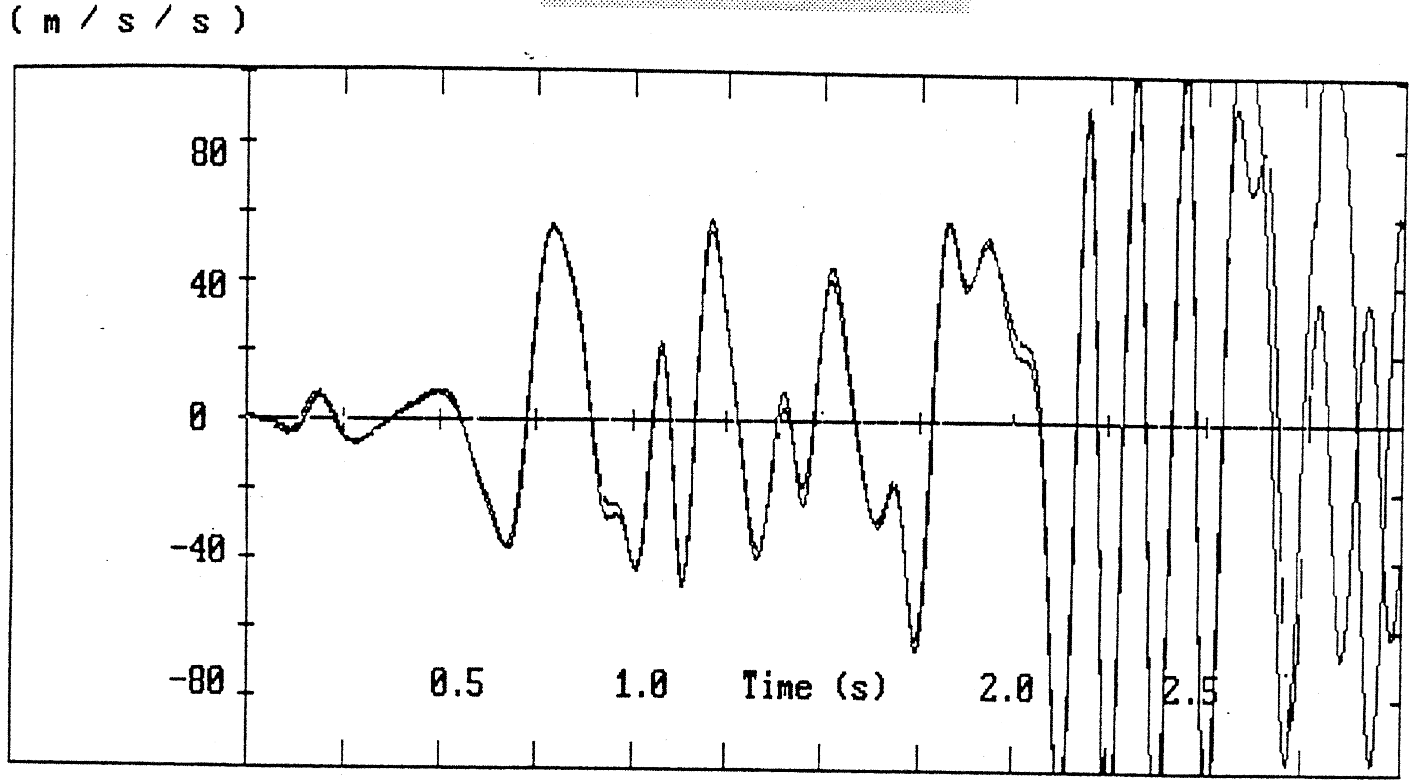
Table 3. Characteristics of Selected Dives from the Reverse Group at the World Diving Cup 1991.

Diver	Dive	Round	Score	Fulcrum Setting	Hurdle Flight Time (s)	Estimated Vertical Velocity (m/s)	Take-off Support Time (s)
Lenzi	305B	T	7.4	7.75	0.78	-3.9	0.49
Lenzi	305B	S	6.7	8.00	0.77	-3.8	0.48
Bradshaw	305B	T	6.4	8.50	0.82	-4.1	0.46
Bradshaw	305B	S	4.5	8.00	0.82	-4.1	0.43
Lomanovskiy	307C	T	7.3	7.25	0.81	-4.0	0.46
Lomanovskiy	307C	S	6.8	7.25	0.79	-3.9	0.45
Platas	305B	T	7.4	8.00	0.75	-3.7	0.42
Platas	305B	S	7.4	8.00	0.76	-3.8	0.43
Lashko	305B	S	6.6	9.00	0.78	-3.9	0.44
Lashko	305B	F	7.5	9.00	0.75	-3.7	0.44
Bartova	305C	S	7.5	3.50	0.64	-3.2	0.43
Bartova	305C	F	6.2	3.50	0.64	-3.2	0.45
Baldus	305C	S	6.4	5.00	0.72	-3.6	0.38
Baldus	305C	F	6.4	——	0.72	-3.6	0.37
Lindner	305B	S	7.3	7.50	0.71	-3.5	0.44
Lindner	305B	F	6.2	7.50	0.72	-3.6	0.43
Depiero	305B	T	6.3	5.00	0.66	-3.3	0.41
Depiero	305B	Q	4.5	5.00	0.70	-3.5	0.38

the diver's downward velocity in the hurdle is added to the already downward moving board.

Reduction in Final Resistance to Upward Board Motion.

In some acceleration patterns, an upward deflection in the curve was noted immediately before the end of the take-off. Although this final small upward deflection was more commonly associated with take-offs of dives from the reverse group, it occasionally was seen in take-offs for forward rotating dives. A rapid increase in acceleration of the board tip at this point in the take-off would indicate that the board suddenly began moving upward faster, likely as the result of a reduced resistance to its upward motion. Such reduced resistance could occur if divers allowed their knees to flex prematurely. In the case of dives from the forward group, it might be associated with an increasingly rapid downward rotation



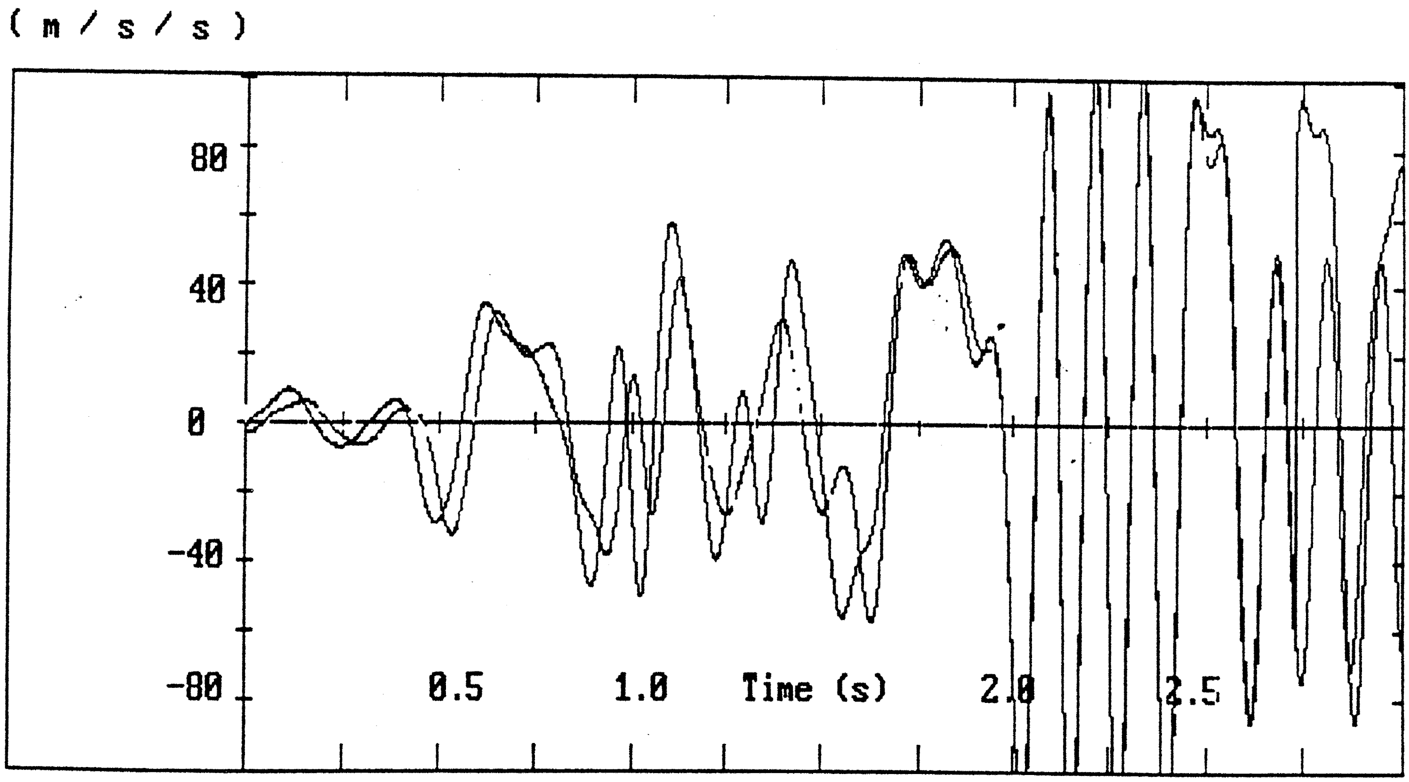


Figure 5. The consistency of the performance of Britta Baldus' 305C (top graph) from the semi-finals and finals at World Diving Cup VII. Mary Depiero's performance of the 305C during the team and quarter-final competition do not show the same degree of consistency.

of the upper body in an attempt to help initiate the somersault.

Consistency.

Superimposing the acceleration patterns of two performances of the same dive for a given diver was an effective way to qualitatively assess consistency of performance (Fig. 5). Greatest consistency was evident during hurdle support. The most highly skilled divers also had virtually identical vertical board oscillations during hurdle flight. Few divers were able to maintain this degree of consistency through the support phase of the take-off. The latter exhibited the greatest intra-diver variability for a given dive.

CONCLUSIONS

With current computerized digitizing technology, coaches can be provided with reports on selected mechanical aspects of springboard take-offs within a few weeks or even a few days of a competition or data collection session. This technology, however, is unable to give biomechanical information during practice sessions, a feature which would be useful to coaches of national and international caliber divers. Consequently, the development of an accelerometer based data collection and analysis system which was considerably less labor intensive and time-consuming than quantitative video analysis has the potential for providing meaningful feedback on deck immediately after the performance of a dive.

While the system developed was capable of assessing the temporal components of the hurdle and take-off with greater precision than conventional video which has a substantially slower sampling rate, only the beginning and the end of hurdle flight could be consistently identified on the accelerometer record. Consequently, quantitative information obtained from the accelerometer was limited to hurdle flight duration, estimation of the diver's downward velocity at the end of hurdle flight, and the duration of the period beginning with board contact at the end of hurdle flight and including the period of positive acceleration associated with take-off support. The major contributions of the system in providing feedback on boardwork lay in providing information on how the diver 'catches the board' and the relative consistency of a diver's hurdle and take-off performances.

Because of the hardware and software requirements of the system, it is not at present feasible for use by individual coaches and/or clubs. It could, however, provide valuable immediate feedback on diver's boardwork if installed at a national training center or used during national team training camps.

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