THE FORCE PLATE IN SPORTS BIOMECHANICS RESEARCH

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There is an increasing need in research for reviewing and summarizing similar studies. While there has been a preponderance of force plate (FP) analyses of walking, running and jumping, twenty different sports have been analyzed by biomechanics researchers utilizing a FP for study of various reaction force parameters (Table 1). For several sports, only one or two FP articles were found; thus indicating the need for additional kinetic research of these and other sports.

The FP is a biomechanics research tool capable of detecting ground reaction forces (GRF) of a subject in contact with the plate. Generally, the FP contains four sensing transducers, one located in each corner of the plate. Ideally a FP system, which consists of the FP, amplifiers, a computer, and method to display the data, measures, records, and displays forces and torques in three dimensions. As determined from this review of the literature, the FP most preferred for the analysis of sport related performance, since approximately 1970, has been the Kistler multi-component piezoelectric force plate (original 9261 and current models). Researchers tend to note the performance characteristics of the piezoelectric plate over other instrumented force measuring devices as reasons for the successful use of the plate.

This paper examines the contributions of FP research toward an improved understanding of sport performance. The purpose of the paper is threefold: 1) to quantify the sport FP research, 2) to summarize findings related to improved sport performance, and 3) to further the use of the FP in biomechanics and foster methodological and application ideas among sport researchers.

Other areas related to sport performance which also utilized a force plate, including technique modelling and optimization, neuromuscular balance, and shoe/surface design, are not addressed in detail in this review. This article focuses principally upon specific sports where a FP was used in the analysis. Sport summaries have been catagorized into three sections: locomotion, body manipulation, and projection.

LOCOMOTION

The greatest single use of the FP in sport research has been in the study of running. Researchers from several institutions; including the University of Calgary, University of Oregon, Penn State University, and Nike, Inc., have extensively studied various GRF aspects of running.

Running Vertical Impact and Footstrike Patterns

Bates (1982) summarizes his laboratory's research on lower extremity function during treadmill and overground running. The overground condition utilizes a Kistler FP which is securely mounted onto a frame surrounded by a large block of poured concrete. A rigidly mounted plate, separated from the surrounding floor, is crucial for obtaining accurate data. Two high speed cameras have been used to complement the FP system. Their research concerns have centered on shock absorption, foot stabilization, injury prevention, and running technique.

TABLE 1

VARIETY OF SPORTS ANALYZED WITH A FORCE PLATE

SPORT	AREA(S) RESEARCHED
Boxing & Karate	Gloves, Bandaging, Impact forces
Cricket Bowling	Pitching
Diving (Platform)	Technique, Force Production
Fencing	Lunge
Golf	Shoes, Swing
Gymnastics	Floor Skills
Jumping	High, Long, Triple
Judo	Throws
Racewalking	Technique, Impact Forces
Rifle Shooting	Body Sway
Running	Sprinting, Jogging, Long distance
Shot Put	Thrust, Technique
Skiing	Roller, Downhill, Jumping
Soccer	Kicks, Throw-in
Softball	Batting, Cleat Design
Swimming	Turns, Starts
Tennis	Serve, Surface and Shoes
Volleyball	Spike, Shoes, Jumping Technique
Weight Lifting	Clean and Jerk, Snatch, Squat

Force Plate Research Related and Applicable to Sport Performance:

Neuromuscular Balance	Balance, Coordination, Posture
Vertical Jumping	Power, Technique
Optimization, Modelling	Performance
Shoe, Surface Design	Injury Prevention and Improved Performance

Bates and colleagues (1979, 1981, 1983b) studied subject-shoe interaction and shock absorbency for various types of shoes and the barefoot runner. They found different GRF results for different runners in the same shoes. That is, runners were found to have unique perceptions of "hard and soft, and stable and unstable shoes." The four most important variables for comparing shoes and runners were: maximum vertical impact at foot touchdown, maximum vertical loading which occurs at the second peak of the force-time curve, total vertical impulse, and total medial-lateral impulse. They concluded that knowledge of both shoe and subject characteristics are necessary to fully evaluate a shoe's performance.

Many researchers have determined running peak vertical impact forces (Table 2). Mann and associates (1982) used a FP to compare GRFs of walking and running. Vertical peak force for walking was 1.1 BW as compared to 2.7 BW for running. The antero-posterior and medial-lateral shear forces demonstrated the same basic patterns during both walking and running. An in-vitro study (Berme, 1984) of maximum spinal compressive load found both jumping and running to yield a load of approximately 6 times body weight (BW), while for walking this spinal compressive load was only 2.5 BW. Impact forces from a force plate study should be considered more reliable than from film or video since the FP measures forces directly.

TABLE 2

PEAK RUNNING IMPACT FORCES AS A MEASURE OF BODY WEIGHT (BW)

Author	Speed (m/s)	Peak Impact Force (BW)		Note
Bates et al (1979)	4.2 4.9	1.8 2.4		
Nigg (1985)	-	10.0		Measured and Derived
Berme (1984)	-	6.0		Spinal Compressive Load
Frederick et al (1981)	3.4 3.8 4.5	2.0 2.3 2.9		
Cavanagh & Hennig (1982)	-	4.1 2.7	(left) (right)	For 1 Subject Same Subject
McMahon & Greene (1979)	(varied)	5.0 1.6		Hard Surface Soft Surface
Roy (1981)	3.4-5.4	1.7-2.9		Men & women
Mann et al (1982)	(varied)	2.7		
Fenton (1984)	4.5	2.1		Racewalking

Measuring GRFs of rearfoot and midfoot strikers, Williams (1983) determined that a relationship exists between the magnitude of medio-lateral GRF and foot position at footstrike. One might assume from this finding that midfoot and rearfoot strikers require unique shoe cushioning features to limit deliterious GRF effects in the side-to-side plane.

Dickinson and colleagues (1985) studied barefoot running during fatigued and unfatigued conditions. Fatigued barefoot running (45 min) did not cause greater footstrike forces. GRF curves (Figure 2) were similar to Clarke and associates (1982, 1983b), and Frederick and Clarke (1981) and showed the first peak to be, some 2 BW, which reflects the initial vertical impact or collision force and the maximum vertical peak which represents forefoot loading. No relationship was found between the runner's weight and shock. A significant relationship between shock and height was shown;

therefore, it would seem that if GRFs are normalized, they should be normalized to body height and not weight. In addition, the authors presented an excellent discussion of injury prevention, vibration absorption, and shoe design.

The greatest vertical forces determined in running, were those found by Nigg et al (1985). They found that forces in running acting on the human body can easily reach 10 BW. Some researchers may concur with this comparitively high figure if consideration is given to the additional forces produced by contracting and stabilizing muscles acting at the ankle (Burdett, 1982) and knee at footstrike. One would suspect that when all possible sources of force acting on the ankle are considered (gravity, body mass, and muscular contractions) the total forces acting at the ankle may exceed 10 BW.

In an effort to improve performance and prevent injuries, Mason (1980) conducted a FP analysis to quantify different types of runners by their footstrikes at various running speeds. The footstrike patterns, toe-heel-toe, toe, and heel-toe were not shown to change with alterations in running speed.

In 1980, Cavanagh and Lafortune studied a variety of runners striking the platform at 4.5 m/s^{-1} (6 min/mile). Using five right footstrikes, they found 12 of 17 subjects to be rearfoot strikers and 5 midfoot strikers. The mean contact times were 188 ms for the rearfoot and 176 ms for the midfoot strikers. Interestingly, from 30 ms to toe-off, the pressure patterns of the categories of runners were very similar. Distinct characteristics of the antero-posterior, medio-lateral, and vertical force components were evident for midfoot versus forefoot runners. Implications from these results were discussed at length regarding mechanics, shoe design and evaluation, and injury.

Ability Differences Among Runners

Relatively few studies have been published profiling GRF differences between male and female runners, and runners of varying ages and abilities. One of the first comprehensive biomechanical profiles of elite distance runners was developed by Cavanagh and associates (1985). Results from two 1984 Olympian distance runners were presented. Several variables were determined from a Kistler FP, including vertical and shear components, and COP patterns in relation to the foot outline. In addition, pressure distribution during the support phase was measured with a vertical force component piezoelectric platform (Cavanagh and Hennig, 1982) mounted on top of the FP. These data, together with the GRF parameters, formed an elite distance runner profile. One of the most interesting findings for one runner was large differences between the right and left peak impact forces. These were 4.1 BW for the right and 2.7 BW for the left footstrike, for a nearly 900 N difference (Table 2). This large discrepancy disappeared when the athlete ran at the same speed wearing training shoes. Several implications for shoe design and injury prevention were discussed.

Miller and associates (1981) studied amputee running using a FP. They noted similiarities and differences between runners. Some subjects had trouble creating a flight phase. An interesting discussion is presented regarding prosthetic running limitations, prosthetic design and vertical GRFs.

Fortney (1980) studied GRF patterns of early elementary children. She found significant differences for ages two through six in displacement, velocity, and magnitude of forces, rather than in any temporal measure of force. Matsuo and Fukunago (1983), using three Kistler FPs, and photocells used to monitor running speed, determined through appropriate equations the forward energy of the center of mass (COM), and the total external vertical and lateral mechanical energy, and the external work rate during running. Relational findings comparing GRF values by age, sex, and ability were informative in terms of running mechanics, efficiency, and the ability to adjust to GRFs, thereby decreasing vertical impact, and potential injuries.

A comparison of force-time curves from 10 skilled runners was completed by Hamill (1981). The subjects ran across a Kistler FP from sprinting to jogging speeds which averaged 7.0 to 4.0 m/s. Several significant differences existed in GRF patterns among different running speeds, for 19 GRF variables analyzed.

Strain et al (1981) compared GRFs of experienced and inexperienced runners wearing a variety of shoes and running barefoot. Inter- and intra-subject and shoe comparisons were evaluated. Results concerning shoe design and running differences were discussed.

Running Efficiency

Attempts have been made to assess FP measures of running efficiency. Hamill (1983) found no significant GRF differences between right and left footstrikes. While this finding advocates symmetrical gait patterns at sub-maximal speeds, Cavanagh and associates (1985) found significantly large (approaching 900 N) right/left differences in vertical impact forces with racing shoes at faster running speeds.

Williams (1980) used a Kistler FP to evaluate various parameters of running efficiency including right and left asymmetries and COP patterns. In this study and another study Williams (1985) found symmetrical and asymmetrical patterns, even though the subjects were relatively equal in ability. It has not been determined whether altering shoes or running style, in an effort to increase running symmetry, will improve performance.

Kaneko et al (1983) used a FP to calculate vertical displacement of COM, and from that determined the external mechanical work (Cavagna, 1975). Internal work was also analyzed from physical measures, and was combined with the external work to provide an estimate of total mechanical work. Mechanical efficiency was determined for sprinters and distance runners. At constant speeds of running, mechanical efficiency of distance runners was found to be significantly higher (65%) than the sprinters 48 percent. This difference resulted from less net energy cost and approximately equal mechanical work at a given speed.

Most of the early FP research on running efficiency was with sprinting mechanics, particularly power output. In an attempt to clear up confusion regarding the efficiency of the support phase of running, Payne (1983) studied 90 subject's footstrike patterns from sprint to long distance speeds. He identified footstrike patterns from film data and measured GRFs with a FP. An interesting case is made for the forefoot runner who exhibits smoother force-time records and should be considered mechanically more efficient than others who create high impact forces when the athlete's COM is in a vertical line behind the support foot. Payne cautioned however, that forefoot running may not be the most physiologically efficient way to run.

Improved running performance through modifications in track composition has been demonstrated by McMahon (1984) and McMahon and Greene (1979). These researchers showed through FP studies of elastic energy and track compliance during locomotion that it is possible to design or "tune" a running track to minimize injuries and optimize performance. Vertical GRFs were 5 BW on hard surfaces and 1.6 BW on soft surfaces. From the FP information, they formulated the model for determination of the best track surface to both reduce impact forces and actually improve running speed. A new track was developed and installed at Harvard University. Results indicated a 2% improvement in times and increased subject satisfaction regarding the comfort of running on this track as compared to conventional tracks.

Wood (1982) used A FP and high speed film to determine the effects of overspeed treadmill training on maximum overground sprinting speed. The overground sprinting speed increased .46 m/s following the treadmill training, but no report of changes in GRF parameters were presented. One might assume that either the sprinting mechanics became more efficient or that the runnner's neuromuscular system became quicker and stronger as a result of the faster workloads. It would be interesting to study which GRF parameters are altered as a result of overspeed treadmill training, and determine if running efficiency can be improved through this type of conditioning.

Injury and Shoe Design

Subotnick (1985) describes in detail the biomechanics of GRFs and running injuries, and notes that excessive running is often associated with running injuries. Stewart and associates (1984) studied GRFs of running under three workload conditions. They found no significant differences in GRF, but some trends existed for 9 of 12 subjects in the first maximum vertical force and average medio-lateral force. Possible implications from this study are directed toward running injury occurence with kinetic alterations from extended workloads.

Scranton and colleagues (1982a&b) used a cholestrerol crystal FP and a Kistler FP to analyze the effects of using arch and heel supportive devices to modify the forces incurred during footstrike. Significant positive alterations in GRFs resulted in certain runners destined for injury. This type of analysis and treatment could be beneficial in the prevention of common overuse injuries, such as plantar fasciitis and shin splints.

In addition to excessive workload, anatomical deficiencies and running shoes have also been implicated in the etiology of various running injuries. A study of the GRF of high arched and flat-footed runners indicated a need to design appropriate footwear to reduce the undesirable effects of impact stresses (Francis, 1981).

Using a FP, Therrien and colleagues (1982) studied the anatomical methods used by joggers to attenuate impact forces. Differences were noted between rearfoot and forefoot strikers. Forefoot strikers did not produce lower loading rates with cushioned shoes as when jogging barefoot. However, for rearfoot strikers, a cushioned shoe was associated with much lower loading rates than when jogging barefoot. The authors suggested that forefoot strikers might be better able to adapt the body to the forces occurring at footstrike. Perhaps different absorbing mechanisms would be enacted for forefoot and rearfoot strikers if several running speeds were evaluated.

Using a FP, Frederick and Clarke (1981) compared impact loading of runners varying in height and weight. Taller runners experienced greater vertical GRF during footstrike. Implications for shoe design in terms of flexibility and cushioning were proposed for runners at both extremes of the height-weight spectrum. Conventional methods of scaling running shoes may not afford the larger runner with enough cushioning, leave the smaller runner with too much cushioning, and decrease the latter's shoe flexibility.

Clarke et al (1983a, 1983b) tested cushioning properties of running shoes with hard and soft midsoles. The peak GRF did not correlate well with midsole hardness. It was suggested by Clarke et al (1983) that subject adaptations were being made according to various levels of shoe hardness. Further, it would always be difficult to ascertain shoe cushioning properties simply because so many people adjust their stride and footstrike under various conditions. Implications for impact forces and fatigue were also discussed.

The Nike Sport Research Laboratory (1982a) reports on FP and film studies of barefoot runners. The greatest vertical GRFs typically occurred during the first 25 ms of footstrike. Several variables were found to influence the amount of impact force during running. Among these were weight and running speed. The heavier runner and those running at greater speeds created larger impact forces. Body height was also found to directly relate to impact force (NSRL, 1982c). Since foot plantar surface area was found not to scale proportionally with body weight or height, and thereby afford more shock absorption, other methods to improve absorption have been designed into running footwear. These scaled improvements include wedge and material designs, midsole thickness and material designs, and air-sole pressure, volume, and configuration designs.

The running community has not been the only group to have benefited from the advances of running shoe design. DeMoya (1982) conducted a FP comparison between running shoes and combat boots. Obviously the cushioning properties of the boot were far inferior to the shoe. Recommendations were provided to the re-designing of the Army boots using similar running shoe features which have helped reduce certain injuries and enhance comfort and performance.

Studies from Bates and associates (1979, 1981, 1982, 1983a&b), reviewed elsewhere in this article, have provided understanding on several aspects of running shoes and injury. Studying many shoe designs and types of runners, they have analyzed, the runner's perception of hard and soft, vertical loading, lateral impulse, braking and propulsive forces, shock absorption control and shoe stabilization, as each relates to injury.

Sprinting

Yoneda and colleagues (1979) compared kinetic data of jogging and sprinting. Double peak vertical force records were noted for both sprint and jog speeds. Interestingly, for jogging the take-off force was greater than the landing force but in sprinting the landing force was greater than the take-off force. The total impulse for the sprinting support phase was less than during jogging. Support phase impulses were found to be greater when skilled runners jogged.

Using a FP, Gagnon (1977) compared kneeling and standing starts of female sprinters. Force and temporal differences distinguished the skilled sprinters. Payne (1968a) used small strain guage FPs as part of the starting blocks. Those with the better starts had stronger rear foot peak forces. The front foot had greater time over which forces could be applied. Using force vector arrows and cine film from which COM was plotted, the initial force acted behind the COM and tended to rotate the athlete upwards, but later in the start it moved behind the COM to rotate the body downwards. By using response time from the gun sound as measured by the first rise in the force trace and film records, race directors may have a method for distinguishing anticipatory false starts. Also, by using this response time, the starter's cadence can be studied and optimized relative to decreasing the chances for any sprinter to gain unfair advantage at the start.

Fukuaga and Matsuo (1981) determined mechanical power values of 2000-2500 w in the forward direction (Pf) and 300-500 w power against gravity (Pv), These values were independent of running speed. Total mechanical power (Ptot = Pf + Pv) related to kinematic angles of the knee and ankle during the negative phase. Some of the power exerted in the propulsive phase resulted from elastic energy stored as the muscles lengthened during the negative phase.

Plamondon and Roy (1984) studied force-time characteristics of sprinting using a Kistler FP. Eighty percent of the variance in sprinting velocity was accounted for by the breaking phase and the time of support. While sprint velocity was influenced greatly by stride length and frequency, sprinting acceleration was most influenced by the time of support.

Mann (1981), and Mann and Sprague (1980) examined film and FP data (vertical and horizontal components and point of force application) of highly skilled sprinters. They presented an excellent discussion of their integration of kinematic occurences during the force-time production of a sprinting stride. The moment results of ankle, knee, hip, shoulder and elbow during the support and non-support phases were also described.

Racewalking

Using a Kistler 9281 FP, Fenton (1984) studied forces exerted during racewalking. The vertical forces were similar to normal walking, but were greater in magnitude. At a 4.5 m/s pace (6:00/mile), the maximum vertical forces averaged 2.1 BW. A distinct difference between racewalking and running was that the maximum vertical force in running is at approximately the 50% point of the support phase while in racewalking the peak occurs immediately at or just after heel strike, during the first 30% of the support phase. Forces in the medio-lateral direction showed the greatest variability amongst subjects and the peak medio-lateral forces in racewalking were similar to those in running, about .3 BW. Implications for the coach and athlete include distinguishing good versus elite technique, racewalking shoe cushioning design, and injury prevention. For example in technique, the elite walkers tended to have a smoother, less abrupt weight transfer onto the supporting limb, and a greater vertical force at heel strike than the good racewalkers.

Cairns (1984) studied various kinetic aspects of racewalking using an AMTI FP. The most unique temporal characteristic of racewalking as compared to running was that the support and non-support phases are of equal duration. Racewalking rules governing legal technique imply that these phases must be of the same duration or the athlete could be disqualified for "lifting." The medial GRF was shown to have increased significantly as a result of compensatory forces necessary to decelerate shifts of the pelvis. Some concern for knee, ankle, and hip injury as a result of racewalking rules was expressed.

Skiing

The FP lends itself to a variety of uses in skiing. However, few researchers have developed techniques that have actually taken the FP out of the laboratory and into the snow. Baumann (1985) developed a unique FP study of leg thrust and force rate during roller skiing. Implications for adjustments of the frictional characteristics of the roller ski were discussed.

Bober (1973) imitated downhill racing, and using a FP was able to distinguish downhill skiing abilities of a variety of performers by their GRFs. In the same work, Bober used skiers imitating ski jumping while GRFs were measured with a FP. From the GRF patterns he was able to identify different elite performers and specialists from regular groups of students and skiers used as subjects.

Oschchelkov and Prilutskii (1979) evaluated forces acting against the supporting ground during the loading and unloading actions of ski jumpers. He optimized unloading of the ski and calculated the degree of loading required for three types of jumps. They also developed a method to determine the force, movement and pressure tendencies of the skis' loading that characterizes the technique of individual ski jumpers.

Summary of Locomotion

The locomotion FP research has provided a variety of valuable information regarding the following: peak forces, cushioning, injury prevention, the design of sport shoes and sport playing surfaces, COP patterns, right-left asymmetries, male-female GRF differences, experienced and inexperienced runner GRF differences, speed versus GRFs, training and GRF changes, and GRFs and footstrike positions.

Not discussed in this section were the many FP studies on walking patterns which are not directly related to sports. However, the large volume of work on walking offers the biomechanics researcher a wealth of methodological information on collecting and reducing GRF data, and basic information on locomotion patterns.

BODY MANIPULATION

Vertical Jumping

Considerable use of the FP in jumping exists throughout the literature. In some of the earliest FP studies, the Sargent Jump and other vertical jump tests were used as a measure of power or power production. Through examination of FP records of vertical jumping it was shown that power (Fv) was not necessarily a correct concept for assessing vertical jumping ability (Adamson & Whitney, 1971). Rather, the force-time (Ft) impulse curve from the FP describes the actual muscular actions required to produce the jump. The Ft integral is the impulse generated by the jump. The shape of the impulse is likely to provide the best indication of the muscular activity associated with the jump. To improve jumping success, a greater peak force must be produced or one must increase the time over which the force is acting.

Soest and associates (1985) studied one- and two-legged vertical jumps of 10 trained volleyball players, using a Kistler FP, film and EMG data. Jumping height in one-legged jumps was 58.5% of that reached in two-legged jumps, although mean net torques in the hip and ankle joints and net power output in the ankle joint were higher in one-legged jumps. The difference in power output was explained by greater muscle activation during a one-legged jump. This research is an excellent example of how an integrated analysis can offer both descriptive and causative information. It might be an interesting follow-up and a check of these normal subjects to study amputee EMG signals and force production during jumping.

The FP has been a unique tool for determining jump height. Hennig and Lafortune (1981), using backwards double integration of the Ft curve, developed a method for calculating jump heights whether the subject left from the FP or from another take-off point. The calculated and actual jump height varied by < 2%. This procedure may be a more accurate method of determining jump height than film, hip center height, or jump and reach methods.

Ae and colleagues (1983) used a Kistler FP to analyze segmental contributions during a running vertical jump from a one-leg take-off. The roles of various segments were discussed in terms of impulse and momentum each one generates. The degree of contribution of the segments changed; e.g. as the approach velocity increased, the contribution of the lower limb increased.

Lees (1981) studied reduction in forces during impact landing from jumping. The process was found to take some 150-200 ms. The information is important to gymnasts, basketball and volleyball players, high jumpers and others regarding injury prevention. He determined segmental contributions to the total force curve during hard-soft landings. The best techniques for impact reduction were exhibited by the ability to optimally decelerate segments. Whether or not one can actually learn to land more softly might be an interesting follow-up study.

Lightsey (1985) and Shetty and associates (1985) developed and validated a method for determining leg power from vertical jumps. A Kistler FP (9261) was used to provide vertical force and average take-off velocity. From these measures, an approximate average power was calculated. This power correlated highly with power determined from a jump and reach test. The authors concluded that the jump and reach field test can be used as a measure of leg power when the jump height data are applied to apporpriate impulse-momentum and distance formulas.

Vertical impact forces from two types of basketball shoes were assessed using a Kistler FP (NSRL, 1982). GRFs were recorded as subjects landed from heights of 18 and 36 inches onto the plate. Significant differences were found between shoes of different midsole composition. These results indicated the importance of providing adequate shoe cushioning systems to help attenuate jump landing forces which can reach levels of 7-10 BW. To further this research, an integrated analysis utilizing film, EMG and FP data, might provide a more complete answer regarding shoe cushioning, since individuals have been shown to respond differently in the same pair of shoes. Perhaps shoe cushioning systems will someday be individually tailored and adjustable based on variables such as jumping ability, flooring, landing response, and fatique level.

Muscle elasticity and temperature was studied by Asmussen and associates (1976). Using a strain guage FP, the heights of the vertical jumps were considerably reduced at the lower temperature (32 and 37 degrees C). However, after a counter movement in the form of a jump down from a height of 0.4m over the FP, the vertical upwards jump was significantly higher in the cold condition. A follow-up study of muscle stiffness and tension development helped to explain the hypothesis that the series elastic component of active muscle is located in the cross-bridges between actin and myosin filaments. Practical implications from this study suggest that an outdoor track high or long jumper might concentrate on certain aspects of the countermovement in cold weather to achieve maximum vertical take-off forces.

Davies (1984) studied power output using a Kistler FP. The methods used to calculate peak power output negate objections raised regarding the use of jumping as a measure of peak power (Adamson & Whitney, 1971). Peak power correlated well with net impulse, and both peak Power (P) and net impulse (I_N) correlated with jump height.

Komer and colleagues (1981) presented a modelling approach for the analysis of vertical jumping efficiency and effectiveness. They discussed the important role of a force generator sequence in jumping effectiveness, and the need to formulate this information early into the jump training process.

Luhtanen and Komi (1978) used film and a FP to study vertical jumping. The take-off velocity was caused by the contributions of segments to producing the greatest forces. Individual percentages of various segment contributions were given and they totalled 76% of the theoretical maximum which was calculated. The authors felt that with proper training and segmental timing, an 8% improvement in vertical jumping efficiency could be realized. Using a Kistler FP (9261) Miller and East (1976) also analyzed vertical jumping segment contributions to vertical impulses generated during the pre-take-off phase. They determined the segment and total body inertial forces over time during the weighting phases.

Mizrani and Susak (1982) studied the attenuation of impact force from a 1.0m and 0.5m fall onto a FP. Landing on the balls of the feet attenuates forces greater than flatfooted landing. The contributions of joint and muscle actions were found to play a major role in reducing peak forces upon landing. Utililzing a FP Szabo and Szmodis (1980) studied successive vertical jumps with and without the use of arm swing. Implications were presented about fatigue, conditioning, and use of arm swing in the optimum performance of vertical jumping.

Tsarouchas and Klissouras (1981) evaluated GRFs of subjects jumping under increased load with added weight, and reduced load conditions using weights, pulley, and a body lifting harness system. Interesting observations were presented about optimal load and greatest velocity of the jump and highest mechanical power output. In general, the kinematic muscle chain, that has to accelerate the body, functions optimally under a natural load that is provided by one's own body weight.

GRFs of 320 fourteen year olds doing vertical jumps were analyzed by Tveit (1976). He found that the less the horizontal impulse, the better the coordination in executing the vertical jump. Subjects using a preparatory counter-movement had better jumps. Interestingly, warm-up exercises did not improve vertical jumping.

Vergroesen and associates (1982) analyzed untrained students and trained volleyball jumpers with a FP under three starting positions, for force, power, and work measures. The well-trained group had higher peak power and jumped higher. No differences in total peak push-off forces were found between the two groups, so the differences in jump result must have been attributed to segmental sequencing.

Zajac and colleagues (1984) studied vertical and forward jumping performance using only calf muscles. Kinetic data were collected from a Kistler FP. They presented a comparison of simulated models and subjects performing the jumps.

Zomlefer et al (1983) varied the initial jumping conditions and trunk load in a FP analysis of maximum vertical jumping height. Joint torques were determined using the GRFs and algorithms and they were compared to EMGs from the leg muslces. Results indicated that relationships existed between jump height and controlling strategies as measured by muscle activation patterns and joint torques to the different conditions.

Long Jump

Ballreich (1973) studied 60 jumpers grouped by ability into three groups of 20. A Kistler FP analysis revealed that the vertical impulse did not affect (to great measure) the jumped distance of the best jumpers. But with the less skilled jumpers the vertical impulses influenced the jumped distance more than the run-up. Analysis of high speed film clarified that the run-up, which includes speed, step length and step frequency, significantly influences the distance jumped by the best group of jumpers. These results were in agreement with Bedi and Cooper (1977) and Cooper and associates (1973) who used a strain guage FP to analyze the long jump. Their results indicated that jump success was directly related to run-up velocity, least time on the take-off board (110-120 ms), greatest thrusting force (105 lb), highest breaking impulse, and greatest vertical forces (1000 lbs).

Luhtanen and Komi (1979) conducted a FP study of the long jump take-off. They found significant differences between ordinary and national level jumpers. The better jumpers produced higher eccentric forces in both the horizontal and vertical directions. In the push (concentric) phase the vertical forces were higher by 43 percent with the better jumpers. Other force-time characteristics of elite versus ordinary long jumpers were discussed. Contact time was significantly less with the national jumpers, owing to the greater run-up velocity.

Pedotti and Rodano (1979) completed an analytic and FP analysis of the long jump. Maximum forces at take-off were 3.5 to 4.5 BW, while duration of take-off was 170 to 200 ms. All force vectors were found to be contrary to the direction of the jump. The shape of the GRF curves at take-off was similar among jumpers, but significant differences were noted between force magnitudes of the best and worst jumpers. Applications were presented to coaches and athletes with regard to training and performance improvement.

Ramey (1970) used a strain guage FP to determine vertical and horizontal components of force, and horizontal approach velocity of long jumpers. Using these results and the impulse momentum equations to determine take-off vertical and horizontal velocities and directions, he found that the horizontal forces at take-off tend to decrease the horizontal take-off velocity. In addition, he also found that the maximum vertical force at take-off was influenced by a combination of force, impulse and mass of the athlete. He described the use of the force-time parameters in assessing performance and providing the basis for quantitative training goals.

In 1972 and 1973, Ramey used measured GRF data to devise equations for long jump analyses, to determine if changes in the take-off velocity increased or decreased the horizontal distance jumped. Maximum thrusting force was found to occur during the mid-support phase of take-off. The total take-off support phase was 200 ms. Information from the FP was useful for determining the magnitude of additional forces required to make jump improvements.

A follow-up study to his earlier work was completed in 1974 by Ramey who calculated angular momentum from film and FP data. The analysis showed how altering components of the momentum equation can affect jump performance: $Mo = V(t) \times (t) - H(t) y(t)$ where Mo = resultant moment, V(t) and H(t) are vertical and horizontal forces.

The somersault long jump which was banned from competition was studied by Ramey (1976). Although relatively dangerous, this jumping technique resulted in longer jumps for certain skillful athletes. The somersault long jump technique placed the feet farther ahead of the COM at landing as compared to conventional methods. Interestingly, the somersault high jump, which is also banned from competition, has produced exceptional high jumps, as more angular momentum can be used to raise the COM. This jump is typically performed by gymnasts, in cheerleading and certain floor exercise stunts.

Ramey (1982a) used the FP to study long jump and triple jumping, and developed mathematical models of the technique. Again in 1982(b) Ramey used the FP in the analysis of jumping and discussed in detail the FP's overall applicability and potential toward analysis of jumping research.

Roy and associates (1973) studied the vertical and horizontal forces in the standing long jump of boys 7-16 years. Maximum vertical force occurred when the COM was changing its vertical direction from downwards to upwards. The increase in resultant velocity with age was due to the increase in the horizontal force component of velocity. The vertical component of velocity remained constant with age. Maximum vertical force for any age was about 2 BW, as compared to 5 BW in the adult running long jump (Ramey, 1973). The increase in force and power from one age to the next was thought to be attributed in part to the increase in body mass, as the acceleration among ages tended to remain fairly constant.

Triple Jump

Ueya (1983) studied sex and age differences in 360 children in the standing triple jump under five conditions using three FPs. The vertical force components became greater from the hop to the step to the jump, in contrast to a running triple jump, in which the hop and jump produce mainly horizontal forces. The beginning of significant arm usage at age 9, and perhaps an increased neuromuscular control explained some of the growth spurt increases in propulsive jump forces at this age. A second growth spurt increase where greater GRFs occurred for boys was from 13-15 and probably was due more to muscular growth. Among the many temporal changes and trends, the contact time for the boys lasted longer for the step, and the step contact time longer than the jump. This was in contrast to the distances covered in each phase. Implications were directed toward the use of the standing triple jump as a general assessment tool for the development of physical fitness and motor ability in children.

Ramey and Williams (1985) studied collegiate triple jumpers using a Kistler FP (9281), and found the vertical forces for each jump phase (hop, step, jump) to range from 7 to 12 BW at touchdown and 3.3 to 5 BW at toe-off. These triple jump forces are considerably higher than those commonly found in running and sprinting (Table 2) and could prove injurious to the athlete unless training sessions are adjusted to allow for a non-fatiguing, high-quality jumping practice.

High Jump

Boccardi and associates (1979) contrasted GRFs and temporal parameters of the high jump, long jump, sprint and walk. The maximum horizontal amplitude of the vector diagram (109 kg) and the greatest mean horizontal component (75 kg) were reached at take-off of the high jump and were against the movement direction.

Hunnebelle (1973) used a strain guage FP to study 24 college students of varying high jump ability. The Ft curve was reduced to four characteristics: 1) preparatory period, 2) impulsion, 3) suspension, and 4) landing and recovery. Distinct differences in slope of the curve, duration of impulses, and vertical force as a percent of BW were evident among good and poor jumpers. Better jumpers have faster impulses and sharper rise in the vertical GRF curve. It was also determined that if the curve is triangular in shape and slope, the subject will probably never be a good jumper. For athlete progress information, the present author suggests recording the FP measures from time to time during training.

Kilani and Adrian (1985) discussed advantages and disadvantages of using a force plate with other instrumentations in analyzing the high jump. While the force plate data provides important information on take-off forces, the data was shown to be more useful when combined with a film or video analysis of segmental movement. The magnitudes and directions of forces and impulses together with the sequential patterning data afford comparisons of mechanical skill in performing the high jump.

Pedotti and Rodano (1981) studied 250 jumps of 13 international level athletes. All force vectors moved away from the jump direction. The resultant force moved from heel to metatarsal region. Maximum GRF was found to be 41 ms after ground impact of the touchdown leg. After the first initial peak, the second force peak reached values of 5 BW. Velocity at take-off was 500 to 900 cm/s, while the mean value for take-off duration was 170 ms which was similar to the 200 ms found by Boccardi et al (1979).

In summary, the use of the FP in jumping research has provided useful information on long, high and triple jumping technique, fatigue and conditioning, landing and take-off optimization, injury prevention, and effective and efficient performance characteristics. In addition, several researchers have used the FP as a device for optimizing jumping progression throughout training.

Swimmming

Nicol and Kruger (1979) used a waterproof capacitance type of FP to study the impulses exerted during four swim turn techniques. In a preliminary test of the FP they found that their vertical force component seemed to compare favorably to the Kistler piezoelectric vertical force component. Few details were given regarding the mounting of the FP in the pool. The authors found advantages with the flip turn and the open freestyle turn in terms of greater impulses produced.

Shierman (1979) used a Kistler FP to study 11 collegiate swimmers performing grab and conventional swimming starts. She measured vertical and horizontal reaction forces through three start phases: initiation of take-off, "gathering" for the start, and the final thrust. Each phase of the force-time curve was also recorded by film. No differences were found between men and women in patterns of force application. Significant differences in the amount and direction of force production for grab and conventional starts were found.

Diving

Hamill and associates (1985) analyzed cine film, and FP data from an AMTI strain guage FP mounted into a runway on a 5 m diving tower. Subjects performed several front and back dives in a piked position with single and multiple rotations. Intersubject differences existed in vertical and antero-posterior forces. A maximum take-off force was exerted for each dive, regardless of the number of rotations in the dive. Other findings were discussed relative to improved platform diving. It might be interesting as a follow-up to determine the extent to which GRFs affect the success of the dive. Does the point of force application influence trunk lean or overrotation? Does a quicker period of time over which the force is applied generate faster twists and rotations? In a sport where performance is largely subjectively evaluated, providing the diver with kinetic and kinematic quantification would assist the coach and athlete understand the objective nature of diving errors and success.

Weight Lifting

Payne (1974) was one of the first biomechanics researchers to use a FP to analyze weight lifting technique. He studied the horizontal and vertical GRF components using a large strain guage FP and the corresponding film record of the clean and jerk. While platform vibration problems may have limited his results, an interesting relationship was shown between the vertical forces and the position of the weightlifter throughout the lift.

Zhekov and Kim (1978) conducted a preliminary study of the vertical and horizontal reaction forces of the supporting base and the feet as measured by a FP, and the vertical and horizontal reaction forces of the bar and athlete as measured from accelerometers. These two sets of force components correlated only at the beginning phase of the lift. Other findings suggested possible improvement areas of technique for the weight lifter.

Connan and associates (1981) studied the principal aspects of the two-hand snatch lift using FP, EMG, and film data. The integration of kinematic and kinetic data helped explain the movement patterns under different lifting loads.

Enoka (1979) studied the pull during the clean and jerk using a Kistler FP. Three phases of the vertical GRF component were developed: 1) Weighting I, 2) Unweighting, and 3) Weighting II. The best lifter produced the largest initial phase of positive acceleration. Positive impulses occurred during the Weighting phases and a negative impulse during the Unweighting phase. This characterized a negative acceleration of the lifter and barbell. The force data combined with high speed film data allowed a clearer understanding of the forces at the knee, hip and low back during the pull. Implications for safe lifting movements were also discussed.

Garhammer and Taylor (1984) studied COP movements during weight lifting. The findings and implications related fairly well to the accepted lifting technique. At lift off, balance should be on the balls of the feet or slightly behind the ball towards the arch. The bar should be kept close to the shank and in essence should move backwards as the knees move backward in the early part of the lift. Once the bar moves above knee height, COP moves forward toward the balls of the feet to counterbalance knee flexion, and with a slight jump, the bar movement continues upwards. Coaches were encouraged to teach the pulling technique of lifting in terms of the fore-aft COP movement related to the bar position.

Most recently, Lander (1984, 1985) analyzed the weight lifting parallel squat using a Kistler FP. He compared three modified bar-weight positions representing different load heights. Results indicated a relationship between a lowered bar-weight system and a reduced stress on the spine. Explanations were discussed relevant to the lifter using a more erect trunk posture. The modified bar techinque resulted in greater stability in the frontal plane.

Fencing

Using a FP, Gebhardt (1981) studied intercollegiate and Olympic fencers for differences in force, impulse, and power production during the fencing lunge. The most skilled fencers produced rapid increases in the three parameters during the initial phase of the lunge movement followed by rapid decline, resulting in a change in vector direction of the horizontal force at the end of the lunge. The skilled group also attained peak power output sooner than the novice fencers.

Boxing and Karate

Joch (1981) looked at GRFs of 70 subjects comprising three levels of boxers. A direct relationship was found between boxing level and punching force, and the latter was shown to increase 26.6 N per one Kp body weight. Punches to the body were relatively harder (85 percent of maximum punching force) than when directed toward the head (75 percent). The impulse transmission took place at the moment of impact. During the follow-through, body mass was shifted to the front foot, with very little weight on the rear foot. Some suggestions for training included not separating upper and lower extremity training, but rather utilizing the whole movement in practice to improve punching force.

Roy and associates (1984) developed a unique use of the Kistler FP to analyze five conditions of boxing punches. Impact forces and speed of punch were compared to barehand and four types of bandages. The bandaged hand significantly increased the impact force. Diachylon had a greater influence on impact absorption than the guage bandage. Impact force increased directly to the thickness of the bandage. Implications regarding injuries to the head and torso were also discussed.

Smith and Hamill (1985) used an AMTI strain guage FP to receive dropped standard boxing and karate gloves at various speeds. The boxing glove produced a higher peak force and a greater time to peak force. The karate glove produced a higher impulse score. The authors also tested the reaction force effects of repeated glove impacting. After 50 impacts (the approximate number of blows in one round of boxing) the boxing glove peak force had risen 96% while the karate glove's peak force values rose only 27%. Suggestions were given for glove materials and design and the attenuation of punching impact forcs. Neither of these standard gloves were considered safe in terms of protection from concussion.

Judo

Tezuka and colleagues (1983) studied GRFs of skilled judoists performing body drop and sweeping loin maneuvers. Average vertical forces for uke (throwee) and tori (thrower) were 1.2 to 1.6 BW; much less than other collision types of sports. The authors were unable to ascertain the most efficient, effective and safe techniques. There were some advantages of the heavier tori compared to the lighter tori in vertical and medial-lateral throw forces and the time of throw advantages.

Harter and Bates (1985) studied GRFs using a Kistler FP (9281) of two judo hip throws, the inner thigh throw and the sweeping hip throw. Pre-throw strategies by the judoka were found to include either a "push-pull" or a "pull-push-pull" technique to initially unbalance the opponent. There were clear differences between the executions of the two throws, although the kinetic and temporal patterns were fairly similar. The most experienced performers were the least consistent, indicating the importance of employing subtle adjustments in response and attack as situations warrent. This study is an excellent attempt at kinetically determining why and how someone weaker can outperform a stronger opponent through the intelligent application of forces.

Gymnastics

Few kinetic analyses of gymnastic skills have been undertaken. Using a Kistler FP and a high speed camera, Bruggemann (1983) conducted an extensve analysis of 40 backward and 26 double back somersaults of 40 skilled gymnasts. Maximum average vertical GRF for the double somersault was 6846 N and maximum horizontal GRF was 867 N. The beginning of the horizontal GRF curve showed a very short interval of propulsion followed by a longer braking period. The results also suggest the importance of performing perfect round-offs and flic-flacs prior to the somersaults for optimal results. One suggestion for further research in this area is an analysis of the gymnast's impact forces using various mats and support lattice work set over a FP.

Kinolik and colleagues (1980) studied GRFs of front aerial somersaults. They determined take-off forces, and angular impulse about the COM. Rearfoot horizontal forces were always positive, indicating constant propulsive forces until take-off. The front foot showed negative forces during the first 65% of front foot support and propulsive forces during the remaining 35% of support. These patterns were consistant for all nine subjects. The maximum vertical components averaged 2.9 BW during rearfoot support and 3.3 BW during front foot support. The vertical forces were thought to produce COM rotation. Resultant force vectors, and angular impulses were also determined for the somersaults. The researchers found no distinguishing patterns of kinetic parameters relative to the best performances. It was, however, evident that the proper timing and pattern of force production was necessary for skilled aerial somersaults and that these results could be useful in coaching this skill.

Kinolik et al (1981) studied front aerial somersaults from hurdle and standing positions. The resultant GRFs were found to be larger during the hurdle position somersault. Propulsive and braking forces were also described. Propulsive forces from the initial hurdle steps were negative, while in the standing aerials they were positive. Other results and implications for coaching techniques were presented.

Ng (1980) developed a three-dimensional integrated cine and FP technique for quantifying various floor exercise gymnastic twisting movements. He studied skilled collegiate gymnasts performing round-off back handsprings into back somersaults with full twist in tuck and lay-out positions. According to the GRFs of the FP, the twists were always initiated from the floor. This finding was in contrast to earlier coaching theorists who felt that turning motions could be initiated while airborne.

Spaepen and associates (1983, 1984) studied three gymnastics movements: back handspring, forward roll, and somersault. They compared FP and film analyses to a model and simulated evaluation. Although Ft curves were similar, some discrepancies existed due to natural frequency differences in the model and spring, and due to derivative inaccuracies.

Rifle Shooting

Neuromuscular control is vital to the successful performance of rifle shooting. Niinimaa and McAvoy (1983) studied three levels of ability in biathletes. Body sway which consisted of horizontal movements of COP was greater after exercise than at rest. Body sway was also found to be much less with the experienced position shooters. Since COP is only an approximation of COM in quasi-static movement, reliability of the measurement was tested by quantifying body sway while at rest on five different occasions. No differences within subjects were found. The force plate could be used as a periodic testing device to measure shooting steadiness under various training conditions.

PROJECTION SKILLS

Shot Put

Marhold (1974) studied shot putting using a strain guage FP, EMG and film. The movement was divided into five distinct phases. From the results, he applied force, temporal, and distance of glide and push-off data to optimize performance of the top-class shot putters. In addition coaching and training suggestions were provided for improving shot put techniques.

Utilizing a large strain guage force platform, Payne (1974) studied the drive and sliding foot moments and the x,y,z forces, and the rear and front foot actions during the shot put. The direction of front foot thrust was shown to be opposite to the direction of the throw.

Zatsiorskii et al (1978, 1981) discussed the controversies on the time phases of the shot put and the optimal trajectory path of the shot. They also found large errors in determining speed and acceleration variables from film. A direct relationship was found between shot distance and the magnitude of strength developed by the athlete interacting with the FP.

Cricket Bowling

Using a Kistler 9281 FP, Elliott and Foster (1984) studied two Australian fast bowling techniques: side-on and front-on categories. Results showed that impact forces of approximately five times body weight occur at front foot impact. Landing of the rear foot, while not measured with the FP would produce similar forces. These GRF forces (5.5 BW) are on the magnitude of those experienced in sprinting (Payne, 1978) and less than those calculated in the long jump (7 BW, Hatze, 1981). The fast bowling lower limb impact forces combined with the upper body actions of flexion, extension and rotation upon ball release, create substantial forces and torques on the lower lumber region. No significant differences in GRFs were produced by the two techniques.

Softball

Messier (1982) studied softball batting performance during three stride techniques. No significant differences were found between each of the three striding techniques and bat velocity. Some significant differences were found in the lower extremity forces and moments among the striding methods.

Messier and Owen (1985) found that the vertical forces of the rear batting foot increased to 1 BW during stride, and 1.6 BW at ball contact. At ball contact, Fx forces were exerted laterally toward the ball. The reaction to these forces retarded the batter's forward momentum, increased stability, and caused the left hip and knee to extend as contact approached. Results were applicable to improved batting technique, and the design of shoes with cleats aligned along the lines of action of the applied resultant shoe forces.

Soccer

A kinetic FP analysis of the soccer instep kick (Abo-Abdo, 1981) revealed that subjects exerted more force with the supporting foot in the vertical impulse direction than in the horizontal thrusting and braking impulse directions.

Asami and Nolte (1983) used a Kistler FP located under the ground surface and along side of the placed soccer ball to determine the vertical forces of the support foot at kicking impact. Subjects were also filmed from the rear and saggital views to determine several kinematic and temporal variables while kicking the ball at maximal effort. The dependent variable, ball speed, related significantly to factors such as foot velocity, foot maximum angular displacement, impact time and others, but not to the vertical force of the supporting foot at impact (Fz). For the kicker this implies that the amount of vertical force used to plant the support foot does not influence the kicking leg's ability to generate maximum ball speed. Other studies have indicated the critical importance of the supporting foot being planted firmly prior to ball impact for the generation of maximum propulsive kicking forces. Further, no pattern of the GRF curve correlated with variables of the kicking limb.

Roberts and associates (1974) developed a model of simulated kicking from film and FP records. They compared measured vertical force from the platform to calculated vertical GRF for the simulated kick. Using a five degree polynomial equation to ascertain the force-time curves, the model and the actual kicks were shown to be similar in shape. Suggestions for future research and methodological concerns were discussed.

Levendusky and associates (1985) conducted a unique study using a Kistler FP to evaluate GRFs of the staggered stance soccer throw-in. Fore and aft and vertical forces were recorded when the lead foot contacted the FP on the throw-in. Force plate and cine film data were used to calculate the maximum distance for the throw-in. The calculated distance was approximately 9.2 m longer than the actual distances. Implications were given regarding optimizing throw-in technique to produce longer throw-in distances.

Tennis

Using a FP, Payne (1974) studied horizontal and vertical forces of both feet of the tennis server. The results were thought to be limited because of the complex shifts of body weight occurring throughout the serve.

In 1983, Tiegermann studied GRFs of tennis shoes on hard carpet and clay surfaces. Implications were presented for tennis shoe construction and optimal coefficient of frictions for tennis surfaces.

Golf

Williams and Cavanagh (1983) developed a very practical and informative study of kinetic GRFs, torques, and COP patterns on golfers and shoes during a golf swing. Different clubs necessitated different GRFs. Few trends were shown between subjects, but similar COPs and GRFs occurred within individuals. Several implications relevant to shoe design were presented. These included modification of the outsole cleat arrangement and inclination, and using different designs for the right and left shoes since each were shown to function quite differently during the swing. Two other shoe modifications suggested were the addition of a valgus wedge, and making a straight continuous heel wedge allowing for larger shoe/ground contact area.

Cooper and associates (1974) studied the golf swing using two small FPs mounted on a larger single FP and synchronized by an electronic signaling device. Five collegiate golfers used three different clubs for the analysis. Findings included:

1) for all the clubs at the top of the backswing, forces were distributed equally between the feet,
2) force shifted to 75% on the front foot at impact.
3) after impact, seven iron continued at 75% force on front foot while driver reverted back to 50%
4) at end of follow-through the force was approximately 75% front foot for all the clubs.
5) vertical forces were greatest during downswing prior to impact (130-150% of total BW), and least just after impact (80% total BW).
6) maximal clockwise force occurred early during downswing while the maximum counterclockwise force occurred early in the follow-through.

Some implications for hitting technique and future studies were discussed.

Weight transfer of twenty golfers of varying skill was evaluated using a FP by Richards and associates (1985). The results indicated that highly skilled golfers place their weight closer to their heels at ball contact, while less skilled golfers tend to transfer most of the vertical force onto their toes at contact. This difference was thought to result from a greater lower body rotation in the less skilled group. Overall group variability was less for the highly skilled group, indicating a fairly common weight transfer pattern among good golfers. In addition the better golfers transferred the center of vertical force farther forward on the target foot during follow-through.

Volleyball

Several FP volleyball studies were found. Adrian and Laughlin (1983) found greater peak forces in the vertical direction during the spike as opposed to either a stationary or moving block. These vertical forces averaged nearly five times BW, and shear forces during the dig were twice BW. The authors concluded that this information should be used to study volleyball jumping and lunging injuries. Volleyball sport shoes should be manufactured to minimize the shear forces and impact, while allowing maximal propulsive forces. An additional study might be designed to determine why maximum vertical forces are not achieved during both the block and spike maneuvers.

Bosco and Komi (1979a&b, 1982) used a variety of athletes, including volleyball players, to compare three different jumping techniques from a FP. The greatest vertical jump was achieved with a preliminary countermovement which allowed a prestretching of the muscles. The authors were not certain if the improved jumping was attributable to a greater use of stored elastic potential energy or to the elicited stretch reflex, or some combination of the two. This question might best be answered by using either film or EMG data to compliment the FP information. Implications regarding muscle stiffness, damping, and spring characteristics were also discussed. These results should be applicable to a variety of sport research situations.

Coutts (1980, 1982) compared two jump techniques for volleyball spiking: 1) hop and 2) step-close approach. A Kistler FP was used to derive 15 variables from force time curves. Significant differences in impulse, temporal, and velocity measures existed between the two styles. However, no significant advantage of the hop compared to the step-close technique in terms of jump height was evident. The hop approach utilized a faster impulse, which may have allowed for a tactical advantage such as in quick-spike situations. Other findings suggest that the hop approach produces greater fatigue and potential injury possibilities since the step-close approach would tend to reduce the peak force by effectively absorbing more of the approach force over a longer time. These findings correspond to those of other vertical jump researchers (Asmussen, 1974, Cavagna, 1971, Komi and Bosco, 1978a, 1978b) who found greater vertical impulses as a result of rapid muscle pre-stretching.

DISCUSSION AND SUMMARY

The widespread use of the FP in sport biomechanics has been summarized herein. Collectively, the emphasis of this research has been on improving performance and preventing injury. While the largest volume of sport FP research has been completed on running and jumping, FP research on other sports has been far-reaching but rather limited in depth. For several sports only one or two FP studies were found. Many possibilities for future research were discussed.

One significant recent trend in sport biomechanics is the movement toward integrated analyses. Few researchers have studied running or any other sport skill from a fully integrated approach; i.e. using EMG, film/video, and FP data synched together on a time basis. However, technological advances and perfection of integrated hardware and software are steering biomechanics researchers in that direction. To fully understand movement in either a static or dynamic situation, one must be able to describe that motion and quantify the internal and external forces causing the motion. To this end, perhaps the most effective use of the FP is when it is used simultaneously with film/video and EMG instrumentation. Some of the most descriptive information from sport biomechanics research as presented in the review, has resulted from this type of integrated approach.

The combination of kinematic and kinetic data acquisition and reduction systems has been a cumbersome and expensive proposition in the past. Winter (1980) suggests analyzing all lower limb joints (hip, knee, and ankle) collectively for running analyses as opposed to limiting the study to any one joint. In the case of a FP study one would have to incorporate film, accelerometer, or EMG to yield complete movement data from these three lower limb joints. The ability to answer many future biomechanics questions hinges on the successful use of a fully integrated analysis approach.

The FP will undoubtedly continue to provide answers to sport related questions and substantiate or refute existing theories and coaching practices. Additionally, use of the FP will cross into other disciplines (e.g. robotics, human factors, and rehabilitation), taking with it much of the earliest methodology and technique applications which have made it one of the most informative research tools in the field of sport biomechanics.

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* Note: Thirty-five slides of figures from published articles were presented by the author as part of this paper at the ISBS meeting in Nova Scotia (1986). The large number of figures was not feasible to include in

the manuscript. Authors of these figures are acknowledged and their work is marked in the references by the first author of the citation being underscored.

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