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Sport Equipment Evaluation and Optimization – A Review of the Relationship between Sport Science Research and Engineering

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Abstract: In current sport equipment evaluation and optimization, most studies consider the body and an equipment together as one system. This is partially because equipment optimization is mainly done through modification of mechanical designs, thus equipment evaluation is conducted through statistical comparisons of how different mechanical designs perform under human usage. However, it is known that any change in the performance environment would cause one to adapt certain aspects of his or her movements. Variation in equipment is considered as such a performance-altering environmental change. Yet, this equipment-induced motor control change is hardly studied in sport equipment evaluation/optimization, such as studies on golf clubs, pole-vaulting poles and hockey sticks. Without a thorough understanding of the interactions between equipment alteration and human motor control adaptation, equipment optimization is like a hit-and-miss game. Therefore this paper aims: 1) to look back at the different generations (eras) in the development of sports equipment, 2) to elaborate the roles of engineering and sport science/motion analysis technology in each generation and 3) to discuss the essence of sport science research in sport equipment optimization, which has evolved beyond pure engineering. One focus of this review is on body-equipment interactions and body movement adjustments in response to different equipment designs. Both these aspects should ideally be included in future studies related to sports equipments.

INTRODUCTION

Sport Equipment Optimization is a major study area for those researching sport equipments and human factors, a sub-discipline of Human Factors and Ergonomics (HFE). In general, HFE focuses on optimizing the interaction of human performers with their work environment. Examples include assessing the mechanical, physiological and psychological demands placed on the performer while doing physical work [1]. Since it is desired that we perform physical activities efficiently, it is crucial to have appropriate equipment designs to support the human performer. A review of the relationship between improvements in human performance and the development of equipments will, undoubtedly, help us 1) to assess our current research methods, 2) to evaluate current equipments and 3) to identify possible directions for further improvements. Boff [2] has recently divided the development of HFE into four generations; they have evolved from adapting human performance to best utilize existing equipments to improving equipment design for biological enhancement of physical or cognitive capabilities. As a sub-discipline of HFE, sport HFE experienced similar, yet notably different development phases. Historically, sport HFE has emphasized more on the engineering and less on the human movement science. A review of the past and the present will hopefully orient and benefit future studies in this area.

Many sports allow the use of equipments that, in the most cases, have evolved over time. It has been known that human performance can be enhanced by intelligent designs of equipments [3]. However, unlike general equipment design, sport equipment design is often limited not by the natural rules of physics but by the man-made rules of the sport. A delicate balance is maintained between the need for tradition and the desire for new technologies. Sport competitions are held under the rules and regulations of the International Association of Athletic Federations (IAAF), which was founded in 1912 and has about 220 member nations [4]. The IAAF put restrictions on the design of sport equipments. An underlying philosophy is that a fair competition should be determined by the physical and technical abilities of the athlete, and not by differences in the quality of the athletes' equipment [5]. For instance, tennis balls have been highly specified by the rules of international Tennis Federation for over a hundred years, driven by a desire for conformity of ball dimension, mass, and playing characteristics [1]. With such limitations on sport HFE, the development of sport equipment research distinguishes itself from other HFE subdomains.

Sport equipment research can be divided into four generations or eras. They are characterized by physical fit, equipment fit, system fit and biological fit. While spanning different time periods, these four generations share a common interest in achieving human physical effectiveness. What differentiates among the generations is a change in the fundamental role of the human subject in human-equipment system integration. During the development of sport HFE, evolving engineering knowledge and new materials & technology has dramatically transformed sport equipment research; but the end-goal of increasing the humans' capabilities during sport activity remains fundamentally unchanged. As sport HFE advances, the adaptation of engineering methods to human movement science is becoming more and more crucial for improving human performance [6]. The most current generation of sport HFE – biological fit – addresses individual biological variation, thereby altering traditional production patterns of the sport equipment industry by shift-

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ing from mass production to customized production (equipment individualization). This new trend introduces a heavy reliance on performance evaluation. For most sport activities, studies are still needed to establish a valid evaluation method.

This review paper aims to 1) illustrate the four generations of sport HFE with examples, 2) identify current difficulties and 3) discuss the essential role of sport science research in sport equipment optimization, which is no longer a pure engineering issue.

PHYSICAL FIT

The first generation of sport HFE was focused on altering the ''physical fit'' of the equipment to match human capabilities and limitations. Its overall goal was to increase human physical efficiency. Researchers in this generation were mainly practitioners with/without engineering background. Through their practices, they were involved in both the study and the application of equipment design. Generally, this generation invented / improved uncomplicated equipments and trained the body to make the best use of the equipments, which were subjected to design limitations.

This first generation had little connection with science and engineering. It was based largely on the experience of practitioners rather than the results of controlled experiments. Such empirical understanding specified the capacities and limitations of human subjects, from which the choice of a better design should be directly deducible. Some representative figures of this era include Adi Dassler, who introduced nail spikes shoes in 1925 [7] and Cy Denneny, who invented curled hockey sticks in 1926 [8].

As these practitioners' new designs became visible through the Olympics and other public sport competitions, people began to realize that changing equipment design would influence human performance. Consequently, engineers became interested in the area. This subsequently promoted the quantitative analysis and development of various sport equipments and the start of sport HFE communities and industry, thereby serving as a critical precursor to the emergence of generation 2.

EQUIPMENT FIT

In large measure, generation 2 was dominated by engineering. Successful examples from practitioners proved that human performance could be enhanced by improvements in the design of equipment. This inspired engineers to apply engineering methods into sport equipment research. Through the involvement of engineering, athletic performance improved. This was especially true for those equipments strongly influenced by aerodynamics, such as javelin, discus and bobsleigh [4, 9, 10].

For generation 2, equipment design contained a significant component of material science and engineering. The continuing changes of sports equipments in past decades were highly connected with the development of new materials. This major impact of advanced materials in innovative designs can be seen in various sports, including tennis with its graphite fiber reinforced polymer rackets, golf with its tungsten weighted clubs, and vaulting with its metal matrix composite inserts and glassy metal inserts in vaulting poles [4, 11, 12]. The greatest advantage of these new materials is their low density, which translates into higher specific strength and stiffness [13]. These properties considerably reduce the weight of sporting equipments. Additionally, the new materials have high torsion strain resistance and toughness. These attractive properties are highly sought after in various sporting equipments.

While breaking world records using new equipment is exciting, not all such engineering changes in equipment design were welcomed with open arms by the sport governing bodies. Some new designs were either endangering other athletes and officials or changing too drastically the very nature of the sport. Consequently, they were quickly outlawed by the rules committee of the sport. The redesign of javelin in 1980s was such an example. New designs in javelin allowed the world record in the men's event to exceed 100 m, which rendered it difficult to hold the event within a standard athletics stadium [14]. Another example was the "klap" speed skate that increased the time and range of motion of each push off the ice, thus dramatically increasing attainable speeds [15]. This gave such an advantage to the country where these skates were developed that there was controversy over the amount of access other skaters had to the new skates. These impressive equipment improvements in many sports introduced concerns that the Olympics may be more an engineering competition than a sporting one [16].

It should be noted that this generation took an almost purely mechanical approach to improving equipment design. No sensory feedback or biological reactions were considered [17]. In other words, sport science or movement science was still under-toned in sport equipment evaluation and optimization.

SYSTEM FIT

Unlike equipment-centered generation 2, generation 3 was concerned with human systems integration. During this era, more sport scientists (or human motion analysts) became involved in the evaluation and optimization of sport equipments. By this time, it was becoming increasingly clear that there is a limit to purely engineering solutions; thus factors of human performance were explored for equipment optimization. The previous equipment-centered view had overlooked characteristics of human movement and thus left unexamined an entire field of parameters that contribute to a more effective sporting equipment design. To improve equipment design beyond materials and mechanical engineering, generation 3 developed human motion analysis technologies to quantify the effects of various sport equipments [6, 17, 18, 19, 20].

Sport HFE is currently in this third generation – system fit – for most sport equipment developments. A general paradigm for this field is for equipment producers to supply numerous equipments of different engineering designs to sports scientists for evaluations. These evaluations most often comprise of quantification of available athletes' movements with selected equipments using motion analysis technologies. The ensuing descriptive/statistical results are fed back to the producers for possible equipment improvements. Some representative works are hockey stick studies by Pearsall *et al.* and Wu *et al.* [18, 21, 22], golf club studies by

Nils *et al.* [23] sport shoe studies by Nigg *et al.* [24, 25] and baseball bat studies by Bahill *et al.*, Noble *et al.*, and Weyrich *et al.* [26, 27, 28].

The statistical analysis / comparisons of various equipments using human-equipment systems are still, to some degrees, mechanical approaches. Rarely do they integrate engineering and sport scientific works and most new equipments undergo engineering tests before marketing [11, 27, 29, 30]. Additionally, human-equipment system results from sports science only reveals the differences among the products and do not identify the causes of such differences. The reveal of the causes needs first to explore the interaction between body and equipment. It is known that any change in performance environment would alternate human motor control [31]. Variation of a sport-equipment is considered an environment change for the purposes of human performance. Yet, equipment-induced motor control change is hardly studied in sport equipment evaluation/optimization. As engineering optimization of sport equipments approach its plateau, a thorough understanding of the interactions between equipment and human motor control adaptation is needed to take the guess work out of equipment optimization. Current and future sport HFE would benefit from closer collaborations between engineering and sport science.

BIOLOGICAL FIT

The budding fourth generation of sport HFE will likely focus on biologically altering or modifying human physical capabilities to maximize the effectiveness of human performance. There will likely be a marked shift from building better engineering solutions to enhancing biological functions for better performance. While generation 3 is currently focused on identifying optimized equipments through human motion analysis tests, generation 4 will likely attempt a tightly coupled neural fit between equipments and human motor skills. Based on the diversity of anthropometry and variation in individual motor control [32, 33], it is reasonable to assume that Biological Fit will be an individualized rather than a statistical procedure. Therefore, in the coming era, major works may wish to concentrate on: a) development of quantification technologies for identifying the effects of human-equipment interactions on motor control, b) explore biological/motor control adaptation to equipment variations and c) creation of mathematical/computer models to predict behavior of the locomotion system in systematically altered situations [17].

The works of generation 4 is still in its infant phase. Few studies have been reported. An early example was the call for smaller tennis rackets that more closely matched the muscular strength of young players [34, 35]. While visionary, it did not receive much attention from the research society. Another example is the study of how position of crew members influence the aerodynamics performance of bobsleigh [10]. The results showed that optimization of the crew configuration and padding could reduce the competition time by 0.3 s. The third example is a research on Golfer-club interactions during swing and its influences on motor control strategies employed by advanced golfers [36]. The results indicated that the transfer of Center of Gravity (COG) during golf swing was influenced by both golf club type and individual motor control strategies such as timing and coordination of joints. These results suggest that equipment optimization should be linked to both anthropometry and motor control pattern of the end-point users. The large variations found in anthropometry and motor control patterns could render pure engineering improvements ineffective in practice. This was demonstrated by the results of a study done on hockey sticks by Lomond, Turcotte & Pearsall [37]. The research project examined six models of carbon-fibre composite hockey sticks, with both right- and left-handed blade curvatures, from three industry-leading manufacturers. The data indicated that contrary to popular and industry opinion, different construction parameters of blades currently on the market did not alter the blade's global position or orientation (either positively or negatively) during the slap shot.

It should be noted that the chronological period of these four generations is not necessarily identical for all types of sporting equipments. For certain sport disciplines, there exist long transition periods in which multiple generations coexisted. As elaborated above, the generations are defined by the roles of and/or relationships among a) empirical approach, b) engineering and c) sport science in equipment development and optimization. The following review examples from different sport disciplines illustrate how the generations progress. They also demonstrate that sport equipment evaluation and optimization has entered into an era of where engineering and sport (or human movement) science meet.

EXEMPLARY DEVELOPMENTS OF EQUIPMENT DESIGN / OPTIMIZATION IN SPORTS

Pole Vaulting

The IAAF competition rules state that the pole may be of any length or diameter and constructed from any material or combination of materials [38]. Originally, pole vaulters used solid wooden poles made of ash, fir, spruce, or hickory [39]. These poles were relatively heavy and consequently were not conducive to producing a fast run-up. Development of the pole entered into the first generation in the early 1900s, when most good vaulters started using bamboo poles [4]. A bamboo pole is hollow and therefore much lighter than a solid pole of equivalent structural strength. A lighter pole allows the vaulter to achieve a faster run-up, which improves athletes' performance. The second generation began in the 1940s as durable and slightly flexible poles made from Swedish steel replaced bamboo as the most popular material among the world's best vaulters. In the early 1960s performances rapidly improved with the relatively rigid poles made from steel. With the invention of more and more new materials, pole performance was improved via new engineering products. Perhaps the most notable example of innovation in athletic equipment is the flexible fibreglass pole. The main advantage of a flexible pole is that it reduces the shock experienced by the vaulter when the pole is planted for take-off [40]. Starting in the early 1990s, carbon fibre has been used in some poles for body wrap section. The carbon fibre maintains the mechanical properties of the pole, but reduces the weight by about 15-25%. Although lighter than fibreglass poles, carbon fibre poles have not yet been universally adopted [4].

Currently, vaulting pole evaluation and optimization is in the third generation. The modern poles are constructed from fibreglass or a mix of fibreglass and carbon fibre. These poles may be bent by over 170º without breaking and are able to store an amount of elastic strain energy that is equivalent to about one half of the athlete's run-up kinetic energy [40, 41]. Pole vaulters do not need a highly flexible pole to successfully perform a pole vault (a rigid pole will do), but they can achieve a considerably greater height through choosing a pole with an appropriate stiffness. With a flexible pole the athlete must take into account the timing of the storage and release of energy in the bent pole. Two aspects considered when deciding the pole stiff are 1) poles must minimize the loss of kinetic energy when planted for take-off and 2) poles must return the stored energy to the athlete in a timely fashion [42, 43]. If the pole is too flexible, the athlete will reach peak height at a location beyond the crossbar; conversely, a pole that is too stiff will bring the athlete to peak height before him/her reaches the crossbar. The optimum pole length and stiffness is different for each athlete, and depends on the athlete's run-up speed, body weight, vertical reach, and vaulting technique. This is clearly a multi-disciplinary problem, where motion analysis science cannot be excluded. The individualized quantification of an optimized pole could be achieved through integration of relevant parameters into a mathematical/computer model, which may be a research direction that would lead vaulting pole research into generation 4.

Golf Club

Before 1970s, physical fit was the main aim for golf club designs. Starting in the 1970s, engineering gained prominent roles in club improvement, indicating development of generation 2. During this period, golf clubs were often designed with a focus on mechanical club properties and launch data [44]. Such engineering-based approaches are still in practice today. The industry is currently varying their club shaft length and elasticity, center of mass and club head surface properties [11, 23, 29]. While these efforts address well the mechanical aspects of a golf swing, they do not consider human factors and the biomechanical / motor-control components. Since the 1990s, more and more club studies involving actual human subjects have been reported, signaling the start of generation 3. These studies were mainly focused on the influences of different club types on a swing, such as kinematic characteristics of 5-iron, 7-iron, 9-iron, a driver and pitching-wedge [45, 46] or three-dimensional trunk range of motion for driver and 7-iron swings [47]. It was found that golfers did not change their stance when swinging 5-irons that only differed in shaft stiffness [48]. In contrast, players did adapt their swing to increases in driver shaft length with an increased feet-to-ball distance, thereby avoiding changes in their body posture [49]. A recent study using synchronized data collection of 3D motion capture and ground reaction measurement had successfully revealed the effect of body-equipment interaction on motor skill control [36]. The results indicated that equipment-induced motor control change is related to both equipment mechanical characteristics and individual motor control style. The results clarified that a tightly coupled neural fit between equipments and human motor skills can not be achieved through pure engineering approach. Thus collaboration with motion analysis science is necessary.

Technology has changed the construction, materials and appearance of golf clubs and balls over the last 30 years. Except the introduction of the large-headed driver that has led to significant improvements in driving distance, other alterations have only led to relatively small improvements when tested with human subjects [50]. The results of generation 3 suggest that there are other factors affecting the statistics. In general, engineering improvements are confirmed by tightly controlled objective tests. Due to interactions between body and equipment, variations in human motor control, and other unknown factors, purely mechanical modifications often do not show any statistically significant improvement in practice. Establishing a scientific methodology for quantifying body-club interactions and equipment individualization based on one's anthropometry and trained motor control pattern are possible research directions for Generation 4.

Sport Shoe

Current evidences suggest that generation 1 in the development of sport shoe began in the 1920s, when Adi Dassler (founder of Adidas) made the use of weight-saving materials and introduced nail spikes and hand-made studs to special shoes for track and field athletics and for football [7]. Until 1970s, physicial fit was the main driving force for developments of sport shoe. Remarkable milestones included the first tennis shoe in 1931 and 30 different specialized shoes for eleven types of sports in 1973 made by Adidas.

Generation 2 began in early 1970s, when fitness and running activities started to thrive [51, 52, 53]. Around the same time, research on footwear came to attract movement scientists. As such, generation 3 actually coexisted with generation 2. Initial work concentrated on the kinematic analysis of the foot and the lower extremities [53, 54] and energy considerations of running shoes [55, 56, 57]. These studies established variables relevant to running, leading to the concepts of cushioning, rear-foot control and guidance. The results suggested that running shoes should be built to reduce impact loading and to reduce foot eversion as well as guide take-off inversion [17]. However, recent studies challenge that paradigm for movement control, suggesting that foot eversion/pronation should not be minimized in order to relate joint movement and corresponding muscle activity to a "preferred movement path" [58]. As stated by Nigg, the research so far was often still descriptive /statistical and functional correlations between biomechanical variables and performance related outcome was not available [17].

Addressing biological adaptation in generation 4 could possibly make substantial steps forward. It is known that every force acting on the human body sends signals to the various tissues. Some of these signals may be responsible for bio-positive or bio-negative effects in structures of the locomotion system. As such, motor control and its functions could be altered. Understanding the effects of such signals and knowing how to send the right signals may be a strategy for performance improvement [17]. The first challenge for generation 4 is to develop methodology for quantifying the biological adaptation. Current knowledge in this area of research is very limited.

Hockey Stick

A main goal for hockey stick development, like that for golf club, baseball/softball bat and tennis racket, is to improve the efficiency of energy transfer. The first generation made only a handful of major developments in hockey stick design between the 1920s and the 1960s. It was said that Cy Denneny of the Ottawa Senators (Canada) invented curled hockey stick by bending the blade in hot water and then shaping the blade by a cooling process. He tried his bending stick during the 1926 and 1927 NHL season [8]. The next significant change did not occur until the 1940s, when laminated sticks were born. These new sticks had layers of wood glued together and sandwiched to create a more flexible and durable design. Thereafter, engineering entered into hockey stick production, indicating the arrival of generation 2. The addition of lamination layers continued, though now consisting of new materials like fiberglass or other such synthetic compound. These engineering solutions further added to the durability and performance of the stick, dramatically changing the physics of players' shots.

As a variety of hockey sticks became marketed, scientists in motion analysis adopted an interest in exploring the differences in the different marketed sticks in practice, thus starting the third generation. Since the late 1970s, numerous works have made an effort to define the overall role of the hockey stick shaft, including the effects of various shaft properties such as stiffness and construction materials [18, 22, 59, 60, 61, 62]. Additionally, studies were also made to provide a comprehensive examination of the blade's response during shooting [37]. The results of both types of research were surprising. Contrary to popular and industry opinion, the different construction parameters of blades currently on the market did not alter the blade's global position and/or orientation (either positively or negatively) during the slap shot. Similar results were obtained from studies examining shaft material and construction methods, demonstrating no significant differences in performance [18, 22, 59, 63].

The current scenario of hockey stick development is similar to that of the golf club. One reason could be the lack of coupled neural fit between equipments and the human subject in engineering development. Unfortunately, even the method for examining the mechanism of coupling is still unestablished. Hockey shooting, unlike golf swing, happens during a fast movement state. This exerts considerable challenges for motion analysts aiming to develop quantitative methodologies for examining body-equipment interactions. We have yet to see research paper signaling the arrival of generation 4. Perhaps with new technologies and bright young researchers joining the field, we can expect the era of generation 4 in the near future.

OPPORTUNITIES AND CHALLENGES FOR THE ERA OF BIOLOGICAL FIT

The first challenge in this era is diversity. We have inherited this term with multiple interpretations. On the one hand, diversity is considered to indicate variety and multiformity; on the other, it is associated with the quality of being different. In product design, diversity assumes at least two roles: it can build assurances of variety and choice into its products, and it can also be the source or catalyst for change. Concerning the end-point users, diversity differentiates people as individuals. There are many dimensions in human diversity. They go beyond obvious differences such as race, gender, age, physical abilities, and marital status. Sport motor skill is one of them.

The conservative nature of the underlying philosophy of athletics leads one to be less optimistic about opportunities for developing performance-enhancing equipment. Even so, many equipment manufacturers put considerable efforts into optimizing the design of their equipment within the often quite tight regulations. A product that gives a performance advantage to the athlete, however small, could break world record and that is enough to encourage engineers and sport scientists in this area.

From the viewpoint of sport HFE professionals (sports engineer and sports scientist), it is important to recognize that the process of coupled motor-control fit between equipments and human needs to be addressed and this process can be scientifically optimized. The first step is to develop methodologies to study the mechanism of such coupling. For this, cooperation between engineers and sport scientists is needed. During this phase, we should try to answer the question: is there enough information provided in the research reports about human-equipment interaction, so that the human functions performed and the equipment characteristics involved can be identified?

The next step should be individualized optimization. Statistical concepts become irrelevant in this phase, as it is not powerful enough to address the complicated nature of human-equipment coupling, which is related to numerous factors both from mechanical and human motor-control considerations. The keyword here is individualization. An appropriate method for addressing this key concept can be mathematical modeling, which integrates mechanical, anthropometrical and motor-control aspects. As such, human performance with equipment may be optimized through talent identification (where an appropriate body size and body type is identified for a sport). Via motion analysis and model simulation, motor skill improvements and individualized equipment design for optimized body-equipment coupling can be generated. Through athletic training, the required motor control and perfection of body-equipment coupling can be achieved. One should note that the optimization process may be reiterative.

In summary, the above opportunities challenge the fourth generation of sport HFE. It requires a close cooperation between engineering and sport science. Sport equipment evaluation and optimization is no longer a pure engineering issue; it needs the participation and collaboration of sport scientists

CONCLUSION

Sport HFE can be divided into four generations. The first generation is dominant by practitioners; the second one is the era of engineering; the third one is characterized by coexisting but independent works of engineers and sport scientists; and the most current generation is an era of close collaboration among engineers, sport scientists and practitioners. This trend suggests that as challenges arise from practice, interdisciplinary alliances should be formed.

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