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REVIEW ARTICLE

Biomechanics, Training & Injury Prevention: Considerations for the Taekwondo Youth Athlete

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Abstract

Musculoskeletal injuries are common in many athletic training programs and efforts to limit these injuries are warranted. The purpose of this paper is to: (1) highlight specific biomechanics principles and their relevance to training and injury prevention, (2) summarize research characterizing how various factors affect musculoskeletal structures and injury risk in youth, and (3) synthesize this information into a personalized training prescription model that can be used by those involved in youth Taekwondo. A narrative review of relevant literature is presented, and a personalized training prescription model is developed. Material science concepts and basic research findings related to musculoskeletal injury mechanisms were reviewed along with various injury causation models. The information was synthesized into a personalized training prescription model. The structural/material properties of musculoskeletal structures and the acute and chronic temporal response of these properties to loading vary within and between individuals. Age, sex, and individual genetic differences are factors that influence an athlete's musculoskeletal responses to training and their risk for incurring acute or overuse musculoskeletal injuries. Thus, different athletes can have different acute and chronic changes to musculoskeletal structural/material properties in response to similar loading histories. These concepts were integrated into a personalized training prescription model. The personalized training prescription model provides a useful guide to assist those involved in Taekwondo to develop training programs that assess and adjust various factors affecting injury risk to ensure young athletes receive the greatest sports experience and life-long health benefits.

Keywords: musculoskeletal, acute, overuse, material science

Introduction

Sports participation can facilitate many positive developments in youth (e.g., character, values, discipline, determination, perseverance, academic performance, physical coordination, physical fitness, and physical activity behaviors that can contribute to lifelong health and quality of life), but it can have negative consequences as well (e.g., delinquent behaviors, drug use, and injury) (2, 8, 14, 18). In 2013, The American Alliance for Health, Physical Education, Recreation, and Dance (AAHPERD) made the following position statement, "Young people who play sports are likely to experience physical, psychological, academic, and social benefits, but those benefits do not occur automatically, nor do they occur in the same way for all young people who play sports." (14). The take-home message is that youth sports can provide numerous short- and long-term benefits for the participants, but these outcomes depend on the individual and the sports environment, which is created by the coaches, parents, and peers. Everyone working with young athletes should do everything possible to minimize the negative consequences of sports participation to ensure positive outcomes.

Injuries can be a major negative consequence of sports participation, and preventing injuries is paramount to allow youth to realize positive fitness and long-term health benefits. Athletes of all ages have an inherent risk of injury when participating in sports, but children have unique risks compared to adults. Young athletes experience non-linear growth of musculoskeletal structures that may translate into decreases in flexibility, coordination, and balance. Growth plates and ligament/tendon insertion sites are weaker making them vulnerable to a variety

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of traumatic and overuse injuries (6, 9, 18). Serious injuries can limit short- and long-term participation in physical activity and predispose the athlete to chronic diseases such as osteoarthritis (3), which can reduce long-term quality of life.

Developing effective training programs to maximize desired outcomes and minimize injury risk is complicated and multiple factors must be considered. Effective training programs should allow elite athletes to achieve their greatest physical performance capabilities while minimizing their risk for injury, and allow the average participant to improve or maintain health through appropriate physical activity (i.e., volume, intensity, and mechanics). There is a balance between training dose and health/performance benefits. Too little physical activity contributes to poor fitness and the development of chronic diseases (4). Too much physical activity, or activity performed with poor mechanics, can contribute to injury (9). More children are participating in organized sports in the United States than ever before, but the fitness level of children continues to decline, and these trends likely contribute to the rise in sports-related injuries in children (7). Less fit athletes are more prone to injury. Training response depends on the individual, and therefore exercise volume/intensity should be established based on the individual's goals, intrinsic factors, past response to exercise, and extrinsic factors. Identifying the most effective training program for an individual is not simple, but models are evolving that provide a valuable framework for exploring ways to train an athlete to invoke desired responses (e.g., strength, cardiovascular fitness, and flexibility) without causing injury.

Multifactorial models of injury causation have evolved over the past 25 years to provide a means for studying the complex interactions between injury risk factors, inciting events, and injury (3, 15, 16, 17). Injury risk is affected by intrinsic factors (e.g., age, sex, flexibility, strength, body composition, skill level, fitness level, and injury tolerance), extrinsic factors (e.g., environmental conditions, terrain/surface, coaching, rules, and equipment), and an inciting event (e.g., a certain body motion and/or a certain body loading), the interactions of which have been modeled to provide a framework for studying injury causation and developing preventive measures for a specific injury type (3, 15, 16, 17). The model by Meeuwisse et al. also includes the consequences of repeated participation in sport, both with and without injury (Figure 1) (17). These models provide a solid theoretical foundation for investigations of injury causation as well as a conceptual guide for coaches, including Taekwondo coaches, to consider when training their athletes.

Taekwondo is a popular and growing sport that provides young athletes all the benefits and risks of many other sports. Taekwondo can be performed by elite athletes in a competitive venue as well as average people interested in maintaining fitness

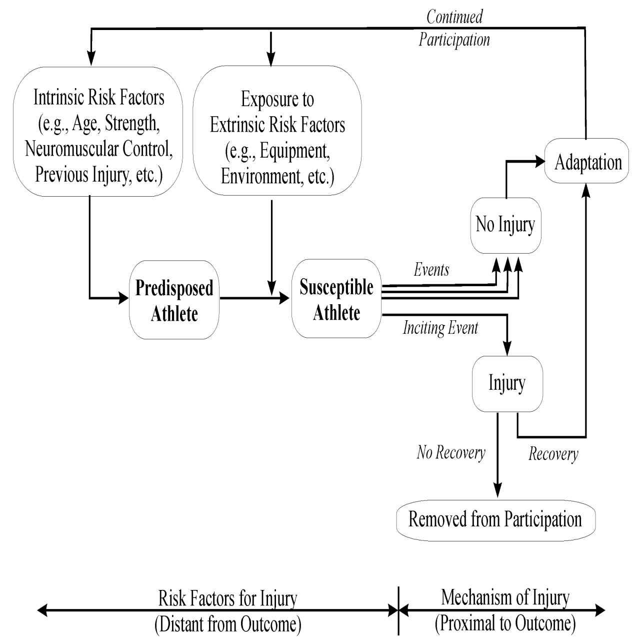

Figure 1: Multifactorial model of injury causation showing interaction between intrinsic factors, extrinsic factors and an inciting event (modified from Meeuwisse et al, 2007 [17]). Intrinsic factors can predispose an athlete to a particular type of injury. Extrinsic factors can expose the athlete to conditions that make him/her susceptible to injury. During training or competition, an athlete is exposed to numerous events, some of which (an inciting event) may cause injury or microtrauma. These events may lead to positive adaptations to musculoskeletal, cardiovascular, and immune systems, but they may also cause negative effects (e.g., acute and overuse injuries).

and health throughout their lifetime. According to the World Taekwondo Federation website (http://www.worldtaekwondo federation.net/popularity), 205 countries practice Taekwondo. The exact number of Taekwondo participants world-wide is not known, but in the United States, there are an estimated 8 million participants in martial arts (25), with Taekwondo and karate being most popular. Taekwondo is considered a relatively safe martial art with respect to acute injuries (22), but little is known about the incidence of overuse injuries.

The unique growth and development characteristics of youth, their declining fitness levels, and changing physical activity patterns make it very challenging to develop appropriate youth training programs to maximize the benefits of sports participation and minimize injury risk. Coaches of Taekwondo and other sports should: (1) understand the basic interactions between training volume/intensity, child growth, movement mechanics, anatomy, the loads imposed on the body during training, the response of the body to this loading, and injury risk as highlighted in injury models (Figure 1) and (2) translate this information into training programs that emphasize movement mechanics and exercise frequency, duration, and intensity that result in appropriate physiological responses that maximize the health and performance of individual athletes while minimizing their risk for injury. Unfortunately, most youth coaches have minimal training in these areas, meaning that our most vulnerable athletes receive instruction from the most inexperienced coaches. There is a need to distill basic and clinical research information into user friendly resources, so those involved in youth sports can create effective training programs.

The purpose of this paper is to: (1) highlight specific biomechanics principles and illustrate their relevance to training and injury prevention, (2) summarize research characterizing how various factors (e.g., age, sex, growth, exercise, and disuse) affect musculoskeletal structures and injury risk, and (3) synthesize this information into a training prescription model that can be used by those involved in Taekwondo training of youth to create more effective training programs.

Methods

To achieve the stated objectives, a narrative review of relevant literature is presented and a personalized training prescription model developed. Basic concepts from material science and Wolff's Law are reviewed first to provide a foundation for understanding structural/material properties of musculoskeletal structures. Basic research studies that investigated the interactions between structural/material properties of various musculoskeletal structures, physical activity, age, and sex are then summarized in the context of injury mechanisms. Finally, this information is synthesized with previous injury causation models to create a personalized training prescription model for young athletes participating in Taekwondo and other sports.

Results

Material science

Structural properties describe the mechanical behavior of an entire structure (e.g., a building support pillar or human femur), whereas material properties describe the mechanical behavior of the material comprising the structure (e.g., the concrete in the pillar or the bone in the femur). Consider a structure (e.g., steel beam, rubber strap, and tendon) subjected to a tensile force (Figure 2A). As the force increases, the structure stretches until the ultimate force and deformation of the structure are exceeded and the structure fails. The ultimate force and ultimate deformation of the structure depend on the dimensions of the structure (i.e., the cross-sectional area [CSA)] and initial length, respectively) and the material making up the structure (Figure 2B). By normalizing the applied force by the cross-sectional area (stress) and the deformation by the initial length (strain), the effect of structure geometry can be removed, thus allowing the material properties (i.e., stress vs. strain) of the structure to be characterized (Figures 2C and 2D). Both structural and material properties of biological structures can change in response to growth, physical activity, and aging and are important considerations when designing training programs. For example, a tendon may get longer and increase in cross-sectional area as a child grows. It may decrease in cross-sectional area if the physical activity level of the person decreases and as the person ages beyond about thirty. The material comprising the tendon may also change (e.g., altered collagen, cross-linking, and water amounts) with changes in activity and age. These structural and material changes affect the strength and risk for injury of a musculoskeletal structure.

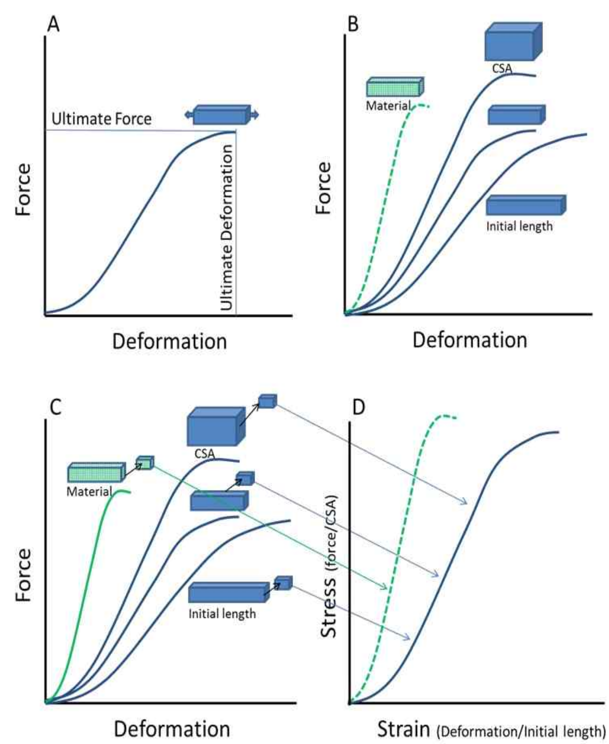

Figure 2: Basic illustration of the force-deformation behavior (structural properties) for a structure such as an elastic band or a human tendon (A), how those structural properties are affected by the structure's initial length, cross-sectional area (CSA) and material (B), and how by normalizing the force by cross-sectional area (stress) and the initial length by instantaneous length (strain) (C), the stress-strain behavior (material properties) are determined (D). Both material and structural properties affect the integrity of a loaded structure. Different structures may have very different structural properties, due to differences in gross geometry (CSA and/or initial length) and/or material properties.

Wolff's Law

Wolff's Law describes the response of biological structures to changes in mechanical stress and represents a culmination of ideas from several people with the name credited to Julius Wolff, a 19th century German anatomist and surgeon (13). The basic idea is that bone in a healthy person or animal will adapt to the loads imposed on it. If loading on a particular bone increases, then the bone will remodel over time to become stronger in order to resist that particular type of loading. The converse is true as well: if the loading on a bone decreases, then the bone will remodel and become weaker due to turnover. Wolff's Law is generally applicable to all musculoskeletal structures with remodeling rates varying with age, sex, and between individuals. It assumes that the loading does not cause failure and sufficient time is allowed for remodeling to occur.

Injury mechanism considerations

The integrity of a functional unit such as a bone-ligament-bone (BLB) or muscle-tendon-bone (MTB) complex depends on the relative structural properties of the individual structures and the loads imposed on them. The structural properties of muscles, tendons, and bones acting in series need to be matched (e.g., osteo-tendon insertion strength needs to match tendon strength, which needs to match muscle force production) to minimize the risk of injury. Unfortunately very little information is available regarding the relative structural properties of muscles, tendons and bones acting in series for the growing child. There is even less information about the interaction between exercise, growth and development, and structural properties.

The limited human data provide evidence that muscle and tendon do not grow proportionally. Elbow flexion (24) and knee extension (21) strength increase on average by a factor of 1.8 between 10 and 15 years of age. However, hamstring muscle tendons and biceps brachii tendons increase in cross-sectional area by a factor of about 1.5 during this same time (10). These muscle strength and tendon cross-sectional area changes mean that tendons operate closer to their failure limits during daily activities as maturity is reached, and/or the material properties of tendons must change during maturation to increase the strength of the material to match the increased muscle strength.

Data from animal and cadaver studies provide insight into the complex interactions between age, activity, and modes of injury for various functional units such as BLB and MTB (11, 19, 20, 23, 27, 28, 29). Ligaments and tendons become stiffer and stronger during maturation (28, 29). These structures withstand greater stress and strain before failure as the loading rate increases (29). BLB complexes tend to fail by avulsion in immature animals and by mid-substance tears in mature animals (28). There are differences in the strain induced in different regions of BLB and MTB complexes. The tendon insertion zone appears to experience twice as much strain as the tendon under moderate stress (23). Tendons become stronger in response to long term exercise, but the cross-sectional area of the tendon does not necessarily increase in proportion to the strength gain (27). This suggests that the material properties of the tendon change in response to exercise. These studies highlight the important and asynchronous rates of structure changes that likely occur in the growing child.

Research studies typically report outcomes in terms of the average response of a targeted population (e.g., young/old, male/female, trained/untrained, etc.), but we need to consider the individual responsiveness, not just the mean response. Recent research in genomics and proteomics reveal that different people have different responsiveness to different training programs (5). These results provide evidence for the importance of assessing individual responses to training and adjusting the training volume/intensity according to these different responses.

Injury mechanisms, progression, and warning signs are important for those involved in Taekwondo to understand, so they can prevent injuries and/or identify and treat them early. In the context of musculoskeletal biomechanics, injury can be defined as damage caused by physical insult at the sub-cellular, cellular, and whole structure level. There are three primary terms used to distinguish the onset and/or duration of an injury (i.e., acute, chronic, and overuse). An injury that results from a singular event (e.g., a large force created by a collision or a sudden movement) and has an immediate onset of symptoms is commonly referred to as an acute injury (e.g., bone fracture, ligament rupture or partial tear, and muscle-tendon rupture or partial tear). An injury that persists over time (e.g., a muscle strain or ligament strain injury that does not heal) is commonly referred to as a chronic injury. An injury that develops slowly over time with symptoms that become progressively worse is termed an overuse injury. In some literature, chronic is also used interchangeably with overuse. Damage caused by overloading a structure is the stimulus for remodeling and increased strength (i.e., the positive adaptations). Therefore, controlled overloading (controlled in terms of magnitude, duration, and recovery time) is necessary to increase structure strength and injury threshold. However, if the magnitude, duration, and recovery time of loading is not well controlled, then acute, overuse, and chronic injuries can occur that prevent the athlete from being able to continue to train at the desired intensity.

One goal of Taekwondo coaches is to design training programs that provide proper overload conditions that result in the desired positive structural adaptations in their athletes. It is important to understand that two individuals performing the same physical activity may generate different forces in their musculoskeletal system due to differences in anatomy and movement mechanics, and there will be differences in the individual structure responses to repeated bouts of loading. All structures have their own loading threshold for injury, which can change and depends on the loading magnitude, duration, and recovery time between loading bouts. Depending on these conditions, structures may become stronger (positive adaptations), accumulate damage (overuse injury), or incur an acute injury (Figure 3). A muscle group may adapt quickly to accommodate increased demands created either by changes in limb inertial properties or changes in physical activity and generate greater force either by increasing its size or activating a greater portion of its mass (positive adaptation). If the tendons and apophyses associated with a muscle group adapt slowly, then the stress induced in the tendons and apophyses will increase in response to the increased muscle force and perhaps lead to microtrauma accumulation, reduced injury threshold, and either an acute or overuse injury. Unfortunately, as previously mentioned, data on the relative strengths and rate of strength changes between muscle, tendon, ligament, and apophyses are lacking for both humans and animals, and there are no proven methods available to accurately predict the responses of individual musculoskeletal structures to a rigorous training program. Thus, an effective training program is the result of the knowledge and diligence of those responsible for training oversight.

A key concept that must be understood by those involved in Taekwondo training is that overuse injuries develop over time and have warning signs. Basically, the remodeling process associated with the response described by Wolff's Law is interrupted, and damage accumulates with repeated bouts of exercise weakening rather than strengthening the structure and causing progressive increases in pain. People responsible for Taekwondo training design and oversight must closely monitor the athlete's training dose and response and modify the training program if symptoms develop (e.g., tenderness at the Achilles tendon or tendonitis), Achilles tendon/calcaneus insertion (apophysitis or Sever's disease), and tibial tuberosity (apophysitis or Osgood-Schlatter disease). Of course, for most people involved in Taekwondo training it is not obvious how to integrate these various concepts into a training program, and there is a need for practical resources.

Training prescription model

Material science and youth injury risk concepts can be combined with previous injury causation model frameworks to create a practical youth personalized training prescription model

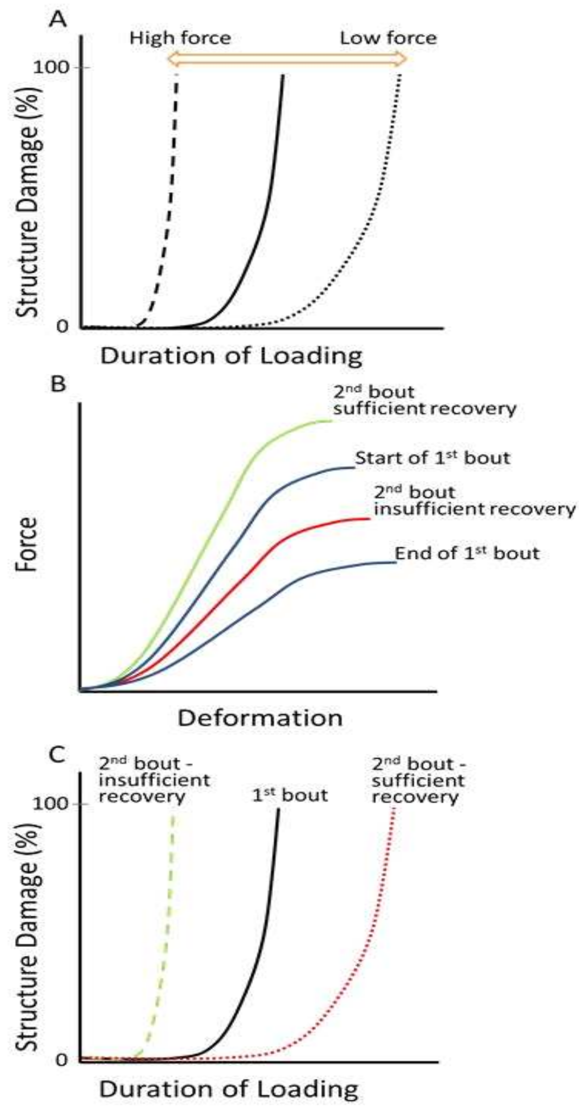

Figure 3: Illustration of the interaction between loading history, micro-damage, and gross injury in musculoskeletal structures. At any time, a structure has a damage vs. loading duration relationship for a given magnitude of loading (A). Damage increases rapidly as the duration of loading approaches some threshold, at which point catastrophic failure occurs. If a single bout of exercise causes minor trauma, then the structure is compromised and the ultimate force of the structure is less at the end of the exercise compared to the start (B). According to Wolff's Law, if the structure is given sufficient recovery time, then it will adapt with increased strength (B), shifting the damage vs. loading duration curve to the right (C) making the structure less susceptible to damage. If the structure is given insufficient recovery time, then the damage vs. loading duration curve shifts to the left (C) making the structure susceptible to further damage. If insufficient recovery time is provided, then damage can accumulate and the structure can experience an acute injury (e.g., bone fracture or tendon rupture) or overuse injury (e.g., stress fracture, tendinitis, apophysitis, and muscle strain).

(Figure 4). Recapping the important concepts affecting training prescription that should be considered in any training model:

(1) The strength of biological structures (e.g., bone, ligament, and tendon) depends on structure size, material making up the structure, and loading history, which can all change (i.e., structures can become stronger or weaker in response to loading and change with maturation and aging).

(2) Structure loading is affected by movement mechanics, which differ between individuals and change with maturation and training.

(3) Loading history can cause positive adaptations or lead to catastrophic or overuse injury.

(4) Injury risk is often characterized in terms of the interaction between intrinsic and extrinsic factors, training events, and the response of musculoskeletal structures to repeated training bouts.

The training prescription model that assimilates these concepts into practical guidelines includes 8 fundamental steps (Figure 4). First, the athlete should be consulted on a regular basis to review the athlete's goals and discuss the training commitment needed to achieve those goals. Second, the athlete's intrinsic factors should be assessed including: his/her age, sex, weight, height, Body Mass Index (BMI), whether or not he/she is growing, his/her strength, flexibility and cardiorespiratory fitness relative to the demands of the sport, whether or not he/she has existing injuries, and whether or not he/she uses proper movement mechanics. A variety of methods that may be used for fitness assessment are summarized by various organizations such as the American College of Sports Medicine (1). Third, the athlete's limb loading history should be assessed by asking the athlete about all his/her physical activities over the past several weeks and whether or not the intensity and/or duration of these activities have changed. Fourth, basic and clinical research should be considered as it applies to the intrinsic factors and loading history profile of the athlete. If the athlete is growing, has pre-existing injuries, or has strength, flexibility, and cardiorespiratory fitness deficiencies, then the training program must address these issues first to minimize injury risk. Fifth, extrinsic factors should be assessed by checking the athlete's equipment and the conditions of the dojang (martial arts training hall). Any potentially problematic issues should be corrected or the training plan should be changed to avoid issues that could not be corrected. Sixth, a training plan should be prescribed for the athlete after thorough

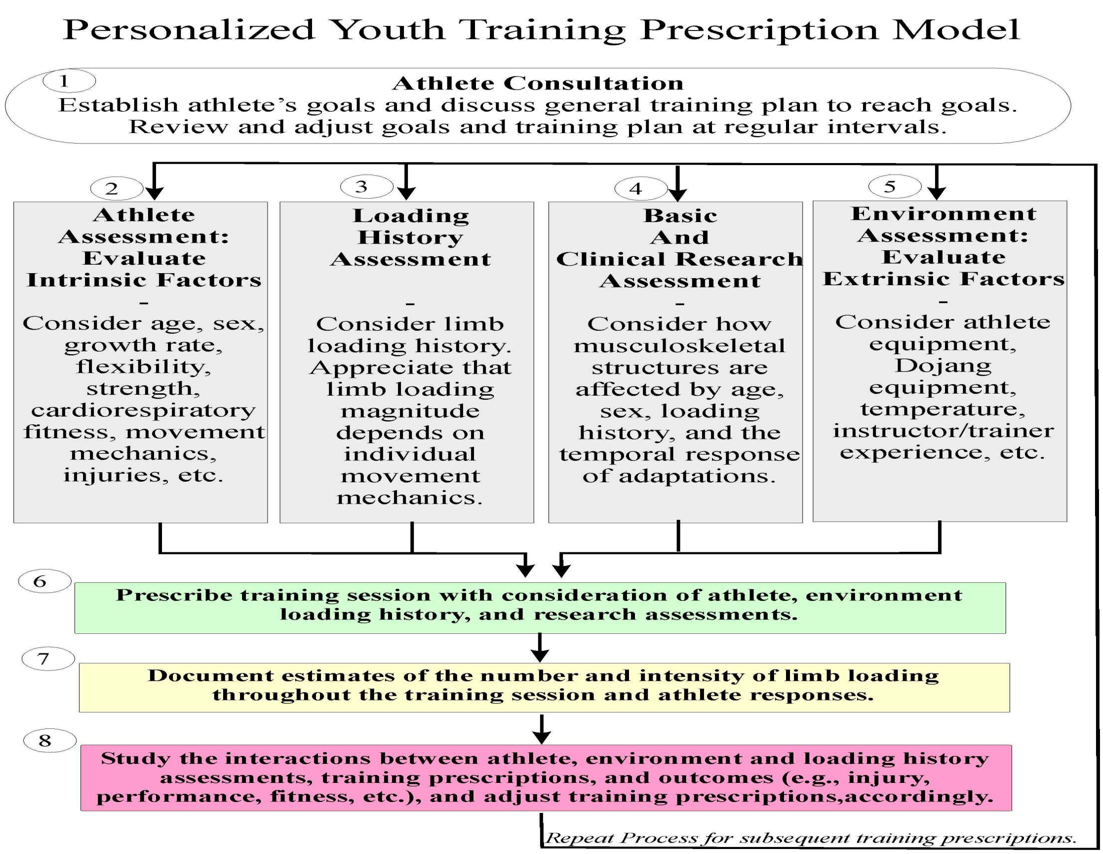

Figure 4: Illustration of the personalized youth training prescription model. Numbered items are described in detail in the text.

consideration of steps 1-5. Seventh, the training session characteristics and athlete responses should be documented for future review. Of note should be the intensity level of the training, the relative number of kicking/punching repetitions compared to other training sessions, the level of contact involved during the training, and the response of the athletes to the training session, both physically (any injuries) and mentally (any signs of burnout). Finally, coaches should routinely review and study the interactions between the prescribed training plan and the athlete, environment, loading history, and outcomes. Learning from these interactions and adjusting the training prescription plan based on the individual responses is essential to helping athletes achieve their greatest performance or health goals while minimizing their injury risk.

Discussion

There are many factors that contribute to injury of musculoskeletal structures including the strength of the structure, the magnitude of the loads applied to the structure, the number of loading cycles, the recovery period between loading bouts, and the rate of structure repair/remodeling. Unfortunately, because of the complex interactions between these various factors, personalized quantitative models that accurately predict training conditions that will lead to injury do not exist. Our current injury prevention guidelines, such as the 10% rule and the limits set for the number of allowable pitches that can be thrown by young baseball pitchers (26), are based on clinical observations and epidemiological data, not an understanding of basic physiology and mechanics or individual responsiveness.

Recent advances in imaging, gene/protein screening, and self-monitoring technologies will greatly improve personalized and automated exercise prescription in the future. Whole body imaging can be performed with sufficient resolution to reveal organ system details (12) that can reveal anatomical characteristics that may be advantageous or limiting for certain athletic endeavors. Rapid gene and protein screening techniques are being refined and applied to predict an individual's responsiveness to various training modalities and injury repair (5). Small physical activity monitoring devices are being developed that will allow people to quantify their loading exposure, heart rate during and following activity, and utilize this information to determine appropriate daily exercise intensities and durations.

Technological advances are exciting, but until these technologies are refined and incorporated into user friendly formats that individuals can interpret, those responsible for physical activity programs (e.g., participants, coaches, parents, and trainers) should understand the interactions between physical activity, age, sex, growth, and overuse injury risk and use this knowledge to monitor and personalize training programs. In 2011, Carter and Micheli wrote:

> While it is ultimately difficult to formulate universally applicable recommendations for training the child athlete, there are several common-sense guidelines that should be followed. In general, fitness training programs for children must be: (1) individual-specific, taking into account factors such as a child's gender, age, BMI, injury history, developmental level and skill set; (2) sport-specific and (3) context-specific, with awareness of the level of play, relevant weather conditions and season length informing all training recommendations. Modifiable risk factors, including poor physical fitness, should be identified and addressed to ensure that children may participate in sporting activities as safely as possible. Perhaps most important is to remember that it is the ultimate responsibility of involved adults-coaches, parents, trainers and teachers-to ensure the health and safety of each child. (7)

These guidelines place considerable responsibility on the "involved adults" without providing a clear implementation strategy. This culture shift in responsibility is important and needs to be taken seriously so that "involved adults" can provide young athletes the greatest sports experience and life-long health benefits. The personalized training prescription model described here provides a practical resource guide to assist "involved adults" to develop training programs that monitor the various factors affecting injury risk and program effectiveness continuously, as summarized by Carter and Micheli (7) and others (3, 15, 16, 17), and adjust the training plan to meet the needs of the individual athletes.

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