Movement Regularity Differentiates Specialized and Non-Specialized Athletes in a Virtual Reality Soccer Header Task

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Funding Source:

NIH: 1U01AR067997-01A1

Take Home Points:

1) Specialized and non-specialized athletes exhibit different degrees of movement regularity when assessed in a sport specific virtual reality environment.
2) The sport specific virtual reality assessment exposed group differences in body movement regularity that were not seen on the DVJ assessment.

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Abstract

Young athletes who specialize early in a single sport may subsequently be at increased risk of injury. While heightened injury risk has been theorized to be related to volume or length of exposure to a single sport, the development of unhealthy, homogenous movement patterns and rigid neuromuscular control strategies may also be indicted. Unfortunately, traditional laboratory assessments have limited capability to expose such deficits due to the simplistic and constrained nature of laboratory measurement techniques and analyses. To overcome limitations of prior studies, we proposed a soccer-specific virtual reality (VR) header assessment to characterize the generalized movement regularity of 44 young female athletes relative to their degree of sport specialization (high versus low). Participants also completed a traditional drop vertical jump (DVJ) assessment. During the VR header assessment, significant differences in center of gravity sample entropy (a measure of movement regularity) were present between specialized [Center of Gravity (COG) SampEn: M = .08, SD = .02] and non-specialized (COG SampEn: M = .10, SD = .03) groups. Specifically, specialized athletes exhibited more regular movement patterns during the soccer header than the non-specialized athletes. However, no significant between-group differences were observed when comparing participants’ COG time series data from the drop vertical jump assessment. This pattern of altered movement strategy indicate that realistic, sport-specific VR assessments may be uniquely beneficial in exposing overly rigid movement patterns of individuals who engage in repeated sport specialized practice.

Keywords: Sample Entropy, Complexity, VR

Introduction

In recent years, young athletes increasingly participate in a single sport for a significant portion of each year and refrain from participating in other sports.[1] This increase in sport specialization may be driven by coaches, parents, and peers who encourage early, specialized practice to enable the achievement of elite performance.[2] However, a systematic review concluded that sport specialization does not result in improved task or career performance compared to non-specialized peers.[3] Many sports, in fact, may allow for intensive, sport-specific training to begin much later in adolescence without detrimental consequences on performance.[4] Furthermore, there are major concerns that early specialization contributes to increased rates of overuse injury in young athletes.[5]

Although precise injury mechanisms remain unknown, researchers hypothesize that immature athletes are less equipped than mature or adult athletes to accommodate repetitive stresses to musculoskeletal tissue.[6] Specialization in a single sport may increase exposure to repetitive stresses that amplifies the risk of injury to the joints and tissue under repetitive load (e.g., baseball pitching and injuries to the elbow and shoulder[7]). Emerging evidence also demonstrates that early sport specialization may introduce maladaptive biomechanical differences between specialized and non-specialized athletes, particularly during maturation.[8] Additionally, highly specialized young athletes are more likely to develop overuse injury when compared to non-specialized peers.[9] Despite this evidence, there are few objective criteria available to quantify appropriate thresholds and diversification of sport participation by young athletes. Therefore, to appropriately inform athletes, coaches, and parents about the risks associated with sport specialization it is vital that the mechanism behind specialization-driven biomechanical change is discovered.

One way to uncover the mechanisms that lead to injury in young athletes is by analyzing the variability of their sport-relevant movement patterns. Movement variability measures capture how an athlete's body moves over time and can offer a detailed picture of athletic performance and potential injury mechanisms. For example, it is not only important to know how many pitches a baseball pitcher throws for a 'strike' or how fast they throw the ball, but also how the form of their pitching movement varies between pitches. Some pitchers may change their movements very little from pitch to pitch, exhibiting highly regular movement patterns, while others may throw differently on every pitch, a more irregular pattern. While irregular movements may be negatively viewed as reflecting inconsistency, they may also represent the offloading of repeated stress onto a larger set of tissues. Moreover, different styles of movement variability result from an athlete's response to evolving circumstances during play and therefore characterizing movement variability may provide valuable insight into the perceptual-motor strategies that athletes use to accomplish their on-field goals.

Movement variability measures are uniquely suited for sports biomechanics analysis due to the ubiquity of high-quality time-series data produced by widely used optical motion capture systems. Analyses of movement variability, however, have often been overlooked in favor of discrete biomechanical and performance measurements such as peak joint angles and moments,[10] with many researchers viewing movement variability as noise or error rather than as an intrinsic feature of a properly functioning system.[11] Although not widely studied in the context of sport specialization, specific patterns of movement variability have been linked to overuse injury.[12] Healthy movement systems exhibit a characteristic mode of variability, which allows the system to overcome unexpected perturbations and adapt to changing circumstances[13] while distributing forces experienced during activity across a variety of structural tissues. Sample entropy

(SampEn) is one nonlinear time-series analysis that has been used successfully to quantify the structure of movement variability, with smaller values of SampEn corresponding to a greater degree of regularity (e.g., a sine function) and larger values corresponding to more irregularity (e.g., white noise). To date, SampEn has been used extensively in movement science and sport science to study posture and balance[14-16], sensorimotor control[17], stroke[18], and concussion.[19,20] SampEn has also provided insight into the dynamics of human gait[21] as well as overall team sport performance.[22]

To complement nonlinear analytic techniques, testing environments should also be appropriately dynamic to isolate differences in movement variability that generalize to actual sport. Immersive virtual reality (VR) is one method that enhances testing by offering an experience that mimics on-field play in a controlled environment that can easily be combined with a laboratory-based motion capture system. Unlike on-field motion-capture solutions, laboratory-based motion capture can be standardized using VR and allow the experimenter to precisely control the perceptual information that is delivered to an athlete. Further, VR offers a significant enhancement to traditional laboratory assessments, which may be too simplistic to elicit the sort of perceptual-motor behavior that characterizes an athlete's on-field play.[23,24] Often, laboratory assessments lack the features of the sport-specific contexts, such as dynamic opponents and objects (balls, goals, etc.), that may drive the movement patterns of athletes.[25] This may be especially true if the athletes have varying degrees of specialization in a particular sport. For instance, a highly specialized soccer athlete may develop unique, possibly detrimental movement patterns in the context of a soccer game that are not expressed during general laboratory assessments. Therefore, a meaningful comparison with non-specialized athletes would require a soccer-specific context. Although not in widespread usage, VR is gaining traction as a useful tool in sports training and assessment [26] and has previously been used to characterize the throwing kinematics of handball players,[27] to identify anterior cruciate ligament (ACL) injury risk profiles,[28] and enhance knee biomechanics after ACL reconstruction.[29]

One notable utilization of VR related to musculoskeletal injury risk was a prior report using a soccer-specific header scenario to identify high-risk lower extremity biomechanics in adolescent athletes.[25] This work identified biomechanical deficits associated with ACL injury that were magnified during the sport-specific VR task when compared to a drop vertical jump (DVJ) task, indicating the possibility that sport-specific VR may be a more sensitive testing method. While simple landing tasks such as the DVJ have been informative about the biomechanics of injury risk,[30] they do not provide the same degree of realism as the sport-specific VR header scenario. While both require a single jump as their main feature, the soccer header scenario is more dynamic and requires continuous sensorimotor coordination of the entire body with “external” virtual objects and stimuli, namely the incoming soccer ball, goalie, and goal. Examining whole-body movement strategies is especially relevant in the context of lower extremity injury (e.g., of the ACL),[31] given the apparent links between upper and lower body mechanics that give rise to deficits underlying injury.[32] The DVJ, on the other hand, is more rigidly structured and requires that the athlete follow formal instructions and perform a relatively simplistic movement. In this study, we aimed to leverage the realism of the previously used VR header scenario to explore movement patterns of specialized and non-specialized athletes. Although heading the ball in soccer is performed infrequently relative to other movements (running, cutting, etc.), significant injuries do occur during this complex task and warrant investigation. Further, we chose the header task here because it requires the athlete to perform a difficult visual coordination task (reflecting the ball off their head and into the goal) in mid-air, while simultaneously requiring an athlete to maintain safe lower extremity alignment with restricted sensorimotor resources (attention diverted towards the incoming ball and away from landing mechanics). The VR header thus naturally extends the demands of the drop vertical jump (i.e., motor control/landing biomechanics) by sharing important classification features (a task that exposes sensitive and specific injury risk factors) and increasing demands on the sensorimotor system (additive neurocognitive constraints). Previous work has compared soccer specific jumping with the DVJ and found them to be significantly different in the precise mechanics used by the athlete.[33] We look to build upon this by improving the realism of the soccer specific jumping condition, namely by employing virtual reality to simulate realistic ball trajectories, requiring movements that are highly similar those performed on-field.

The primary purpose of the current investigation was to evaluate differences in movement variability between specialized and non-specialized athletes using both sport-specific VR and traditional landing tasks. We hypothesized that differences in movement variability, indexed by SampEn, would be present during the soccer-specific VR scenario between specialized and non-specialized athletes, but between-group differences would be less apparent during a traditional laboratory assessment of injury risk (DVJ).

Method

Participants

A total of 91 female adolescent soccer athletes participated in this investigation. While no a priori analysis was performed, prior VR work using 3D motion analysis found significant between-group differences with a total enrolment of 38 individuals, so we enrolled a greater number of participants to exceed the sample size of this prior publication[28] to account for the subsequent categorization and final analyses that would be grouped by sports specialization (~three times larger initial n in present work). Our participants represented a subgrouping of participants in a larger neuromuscular training study of soccer, basketball, and volleyball athletes. The current investigation includes data collected from soccer athletes during baseline testing periods, which preceded neuromuscular training exposures. All participants reported no recent injury or any physical or neurological condition that would preclude them from participating in sports. All participants and their legal guardians provided informed, written consent/assent before the start of the investigation. Institutional review board approval was obtained prior to the initiation of the investigation.

Sports Participation Questionnaire

To classify the degree of specialization of each participant, they were asked, prior to participation, to complete a short sport-specialization questionnaire that has been used in previous work to index an athletes degree of specialization.[9] The questionnaire consisted of the following 3 ‘yes’ or ‘no’ questions: “Could you pick a main sport that you participate in?”; “Did you quit other sports to focus on a main sport?”; “Do you train for a single sport greater than or equal to 8 months a year?”. The number of “yes” answers was tallied such that each participant was assigned a score from 0 to 3. Participants receiving a 0 or 1 were placed in the non-specialized group and those who received a 3 were placed in the specialized group. Participants receiving a score of 2 were considered moderately specialized.

The final breakdown by specialization group was fourteen athletes (32%) in the non-specialized group (age: M = 14.68, SD = 1.2) and thirty athletes (68%) in the specialized group (age: M = 15.04, SD = 0.53). Preliminary statistical analysis confirmed non-significant age, height, and weight differences between specialization groups.

Motion capture data collection

During their participation in this study, participants were outfitted with infrared reflective markers and their motions were recorded using a 22 (DVJ) or 44 (VR) camera motion capture system (Raptor-E, Motion Analysis, Santa Rosa, CA, USA) sampled at 240 Hz. A minimum of three markers were placed on each body segment in a non-collinear arrangement. Landmarks on the participant's anatomy and VR equipment included: four attached to the head (via the head mounted display), sternum, sacrum, offset, and bilaterally on the acromioclavicular joints, elbows, mid-wrists, medial and lateral hands, anterior superior iliac spine, greater trochanters, mid-thighs, medial and lateral femoral condyles, tibial tuberosities, lateral shanks, distal shanks, medial and lateral malleoli, heels, toes, lateral foot, and posterior foot. Participants wore a standardized shoe (Supernova Glide 2, Adidas, Herzogenaurach, Germany), within which the foot markers were embedded.

Procedure

Prior to participation in the virtual header task, participants completed DVJ test. For the DVJ, participants were instructed to hop from a 12-inch box, land and then immediately jump to grab a basketball, which was suspended at their previously determined maximum jump height. Prior to performing the DVJ, all participants saw a demonstration of proper DVJ form by one of the experimenters. Importantly, the experimenter demonstrated that both feet should leave the box simultaneously and land without shifting. Any participant's trials that did not follow this form were repeated, with corrective instructions until three successful trials were completed.

Next, participants completed the virtual soccer task as previously reported.[25] First, they were outfitted with a Vive Pro virtual reality headset (HTC, Taoyuan City, Taiwan) through which they viewed the virtual reality environment and a virtual avatar of themselves, from the first-person perspective (*Figure 1a)*. Immediately after putting on the headset, participants underwent a self-paced familiarization session (5-7 minutes in total) consisting of walking, jogging, and running within the boundaries of the virtual space, meant to acclimate the participants to moving freely in VR while also introducing them to the layout and safety features of the VR environment. Prior work has used a similar familiarization session to effectively acclimate athletes to a virtual environment.[28] During this session, participants were shown the boundaries of the virtual space (*Figure 1b)*, which would become visible if the participant moved outside of the central area of the motion capture space. After the familiarization session, participants were provided with automated audio-visual instructions which introduced the VR soccer header scenario. For the header scenario, a virtual, animated character, located at either the right or left corner of the soccer field, would perform a corner kick aimed towards a spot just outside the penalty box in the center of the field. For each kick, the participant was required to run from a starting position (labeled in *Figure 1b)* and then jump and attempt to head the virtual ball into the goal. The participant saw a total of 6 corner kicks, 3 from each side of the field, including one practice trial for each side. The side from which the ball was kicked was randomly selected in a trial-by-trial fashion. The duration of each trial was identical for all participants. Participants were instructed to time their jump to land on the spotlight, which was visible on the grass in front of the goal (Figure 1 (a and b)). During the header scenario, two experimenters monitored each participant. One experimenter operated the VR scenario from a computer workstation and could see everything that each participant could see while the other experimenter stayed in the open floor area with the participant to give verbal guidance if needed and ensure that participants were always safe. If participants performed the header in an obviously wrong manner (e.g. did not jump or cut in the wrong direction), one of the experimenters would provide verbal corrections.

Data Clean Up and Sample Entropy Analysis

After data collection, all motion capture data was tracked and quality controlled to remove artifacts and spurious data and then post-processed using Visual3D (C-Motion Inc, Germantown, MD, USA). Marker trajectories were filtered using a 4th order low-pass Butterworth filter with a cutoff frequency of 12 Hz, and a 12-segment, 6-degree-of-freedom model was applied to the marker trajectories to compute each tracked segment's position and orientation at each time sample. The model was scaled to each participant's weight and height, and the vertical (Z axis) center of gravity (COG) time series for each DVJ and VR trial was computed as:

$$\text{COG} = \frac{\sum_{i=1}^{12} m_i r_i}{M}$$

where m_i and r_i were the mass and vertical position of the ith segment, respectively, and M was the total body mass.

The COG time series was chosen for SampEn analysis because it exhibits a general profile of movement variability during the header task. Applying SampEn analysis to the COG trajectory is an effective way of indexing the global dynamics of whole-body motor coordination. Each COG time series spanned the duration of a given DVJ or VR trial. All COG trajectories from the 44 participants with complete data were subsequently submitted to SampeEn analysis yielding a single value of SampEn per trial and per participant. SampEn values for each trial were then averaged to produce a single SampEn value per participant and per task. All SampEn values were calculated using a radius value of .01 and an embedding dimension of 1. These parameters were estimated following the procedure outlined by Ramdani et al.[17] For this data, which is largely comprised of ballistic jumping movements, we initially tested larger radius values, but found that the analysis became oversaturated with template matches, resulting in a floor effect where all trajectories produced extremely low values of sample entropy. Although Ramdani et al. do not explicitly test or recommend radius values as low as .01 for quiet-stance postural COP data, there is no recommendation given for ballistic movements of the sort that we tested. For our data, the radius value represented between 10 and 15% of the standard deviation of each time series. Data were not normalized to retain the full profile of the jumping movement. For our analysis, the radius value of .01 equates to a real distance of 10 millimeters, which is well above the measurement precision of the motion capture system.

Statistical Approach

The intent of this study was to compare the regularity of movement variability of specialized and non-specialized athletes on two tasks (VR header and DVJ). Therefore, average vertical COG SampEn values for the DVJ and VR header tasks were submitted separately to independent sample *t*-tests with sport specialization (specialized, non-specialized) as the between group factor. Alpha was set *a priori* at $p < .05$ to determine statistical significance. Cohen's *D* effect sizes were also reported to support interpretation of the magnitude of between group differences. To ensure the integrity of these results, groups were tested for outliers, normality, and homoskedasticity. No significant abnormalities were identified.

Results

Participant removals were done prior to analysis due to age, specialization, and incomplete data (see *Figure 2*). First, data from nine participants were found to be incomplete. Incomplete data resulted from missing markers that prevented reliable calculation of the COG and could not be recovered with post processing methods. For the purposes of the current investigation, participants were placed in non-specialized, moderately specialized, and specialized groups based on the sports participation questionnaire, described above. Participants who were categorized as moderately specialized were not included in the current investigation, leaving 69 participants remaining. Furthermore, due to a drastic inequality of 16- and 17-year-old athletes in the high (15 individuals) and low (1 individual) specialization groups, the decision was made to remove all 16- and 17-year-old athletes from the current analysis. Due to the exclusions based on sport specialization status, age, and incomplete motion capture data a final grouping of forty-four female soccer athletes was included in the current analysis.

For the VR soccer header task, a significant difference in COG SampEn was found between non-specialized (COG SampEn: M = .10, SD = .03) and specialized groups (COG SampEn: M = .08, SD = .02), $t(42) = 2.54$, $p = .015$ $d = .82$. Sample header COG trajectories with high and low relative SampEn are presented in *Figure 3*, showing an example of the greater regularity of body movement observed in specialized athletes compared to non-specialized athletes.

COG SampEn values for DVJ trajectories, averaged per individual, were also compared between the non-specialized (COG SampEn: M = .021, SD = .004) and specialized (COG SampEn: M = .022, SD = .003) groups, and no significant differences were found $t(42) = 1.26$, $p = .21$ $d = .41$. *Figure 4* shows 3 example COG trajectories from one participant performing the DVJ, which are noticeably less complex than even the low complexity example in *Figure 3*. This is also reflected in the lower mean sample entropy values from both groups on the DVJ than the same groups on the header task.

Discussion

The primary purpose of this project was to investigate differences in the regularity of movement variability between specialized and non-specialized athletes during a sport-specific VR jump-landing (soccer header) task and a traditional injury risk assessment laboratory task (DVJ). As hypothesized, specialized and non-specialized athletes demonstrated differences in movement regularity (i.e. COG SampEn) during the soccer-specific header task, but no similar significant differences were identified for the DVJ. The directionality of SampEn differences indicate that non-specialized athletes exhibited less regular movement patterns during the VR soccer header than the specialized athletes. These results also indicate that using VR to engage athletes in similar sensorimotor circumstances to those which take place during real play can provide crucial insights into possible injury mechanisms, which are unavailable using traditional lab-based biomechanical measurements.

The current results show that the body movement of specialized athletes is more regular during a realistic soccer header task than the movement of non-specialized athletes. Our interpretation of this is grounded in the notion that sport specific practice of movements such as the header establish “hard wired” movement patterns that persist and solidify if the athlete does not frequently practice movements of a different sort. While “hard wired” movements may allow the athlete to perform well in drills and possibly even in games, it is also possible that this reduced variability, compared to the non-specialized athletes, over time, would lead to a higher likelihood of overuse injury due to more homogenized muscle activation patterns.[34] Athletes who play multiple sports and participate in a larger variety of drills and on-field scenarios could potentially reduce their risk of overuse injury by offloading the stress and strain of their movements onto more muscles and connective tissues. This hypothesis, however, cannot be confirmed with the current data as no overuse injuries have been reported for the set of athletes who participated in this study. Once this linkage is better understood, we would recommend that biomechanical training interventions to address these deficits be implemented to reduce overuse injury risk. Additionally, within-sport changes to drilling and coaching could reduce the regularity of movement patterns without the need for athletes to take on the responsibility of playing multiple sports. Importantly, these changes to athletic practice apply not only to healthy athletes, but also those who are undergoing rehabilitation. It is vital that these athletes' re-structure their movement patterns during the process of rehabilitation so that they can return to sport with renewed injury resistance.

Beyond overuse injury risk, the difference in movement regularity between specialization groups may be indicative of differential sensorimotor adaptability. Specifically, differences in movement regularity could render specialized and non-specialized differently able to respond to unexpected perturbations that arise during the performance of a soccer header. Theoretical support for this view can be found in the theory of Optimal Movement Variability.[35] This view posits an optimal range of movement variability for a given activity, within which athletes can accommodate disruptions to their activity (e.g. redirection of a ball during a soccer header) without injury. Notably, movement regularity that is both greater and less than the bounds of this optimal range may increase susceptibility to injury. For the current results it is difficult to say, without further experimentation, where this optimal range lies and if the movement variability of non-specialized and specialized athletes is optimal and sub-optimal, respectively. However, the presence of a difference at all indicates that this is a question that requires additional investigation. The current results also show that such future investigations should be carried out using realistic sport-specific

VR tasks to complement traditional laboratory assessments, such as the DVJ. The DVJ and similar assessments may not be ideal as they don't allow athletes to move with the same variety that they would on the field and so they may not elicit the style of movement regularity that would characterize their real in-game behavior. As can be seen when inspecting the movements made during the DVJ (*Figure 4*), this task elicits an almost purely sinusoidal COG movement in the vertical dimension, the regularity of which does not vary meaningfully between groups. Our contention is that this largely reflects the highly restrictive nature of the DVJ task, which may meaningly suppress any individual- or group-specific characteristics of the tested athletes' movement. Contrasted to the DVJ, the sport specific VR header task was much more free-form and allowed the athlete to naturally interpret the task, therefore generating an overall set of movement trajectories that is more representative of the range of dynamics that should be expected from the population that our sample was derived from (female youth soccer athletes). Inspection of *Figure 3* clearly differentiates the VR movements from those of the DVJ. The trajectories from the VR header suggest that the nature of the lead-up to the required jump are an important factor driving the regularity of the athletes' movements. Athletes were only required to cover the distance between a starting point and the location where they met the ball, leaving an appreciable period within which athletes could move in a naturalistic fashion. It is our belief that this provides a window onto an athlete's on-field behavior that has been unavailable to more formalized biomechanical tests (i.e. the DVJ).

Future work may seek to expand on the current finding by probing deeper into the neuromuscular and task organization of sport-specific tasks like the soccer header studied here. While the soccer-specific header scenario used in this investigation provided a realistic context for the athlete, it was not used to directly manipulate the sensory-motor coordination underlying the performance of a header to better understand the underlying mechanism. Additionally, it would also be important to evaluate possible coordination deficits in specialized athletes through peak height velocity and skeletally mature athletes to determine if specialization or stage of development is a bigger risk. Future work could investigate, also, if visual perception (i.e., as it relates to coordination with the ball) during a header task plays an important role in causing differential behavior of specialized and non-specialized athletes' neuromuscular systems. Such work would be uniquely empowered by comprehensive control over an athlete's visual environment that is provided by VR. Along these lines, work using dynamic stroboscopic feedback disruption has been used to differentiate the visuo-motor control strategies of those who underwent ACL reconstruction from matched controls[36,37], demonstrating the essential role of visuomotor control in driving healthy landing biomechanics.

Another interesting direction for future research would be to investigate the specific neurological factors that drive differences in sensory-motor function between specialized and non-specialized athletes. While the differences in gross body movement complexity found in this study are a promising indicator that specialization is associated with distinctive sensory-motor control strategies, there is still much to be uncovered at the neurological level. Future work could seek to understand the neurological basis of the different movement patterns uncovered in this investigation by applying neuroimaging techniques to specialized and non-specialized athletes. Previous work has identified divergent electrocortical dynamics in individuals who demonstrate injury-prone biomechanics.[38] A similar approach could very well identify distinct neurological factors which support movement pattern complexity differences that result from specialized training. Specifically, future work may be warranted to investigate the relationship between an athlete's history of concussion and their movement variability. Concussion is a widespread and deeply impactful sports injury with a long-term impact on an athletes quality of life as well as their risk for future musculoskeletal injuries and could possibly have contributed to the current results, although this was not explicitly measured.[39]

One limitation to the current investigation is the lack of performance metrics to quantify the focus and perception of the athlete on the corner kick. Although 3D motion capture was performed for the duration of the task, no concurrent information about the position of the soccer ball, or the success or failure of the goal scoring attempt were recorded. This makes it difficult to qualify complexity in task or goal relevant terms, which some have argued is critical in interpreting complex movements.[40] Future work could solve this problem by synchronously recording features of the virtual task (ball position, goals scored etc.) alongside the 3d motion capture. An additional limitation of this study was the inequality in number of athletes per group (specialized vs non-specialized). Future studies that focus on youth sport specialization should balance recruitment such that participating athletes fall equally in the specialized and non-specialized groups.

One key consideration that can be drawn from the current work is the potential to utilize virtual reality training to improve movement variability adjunctively to on-field training. In addition, for athletes undergoing rehabilitation or younger athletes who are developing neuromuscular control, virtual reality may be a safe alternative to scenarios associated with undesirable head impact exposure, including physical contact with the ball (e.g. headers) and/or other players. Although head impacts sustained during practice are often sub-concussive, there is still significant concern for the negative long-term effects resultant from repetitive exposure.[41] While one could simply limit head impact exposure by limiting time spent playing, that would deprive athletes from the sensorimotor experience that leads to injury-resistance and the physical practice necessary to achieve desired performance outcomes. In this light, immersive virtual reality such as that used in the current investigation, could offer the opportunity to enhance movement strategies related to sport-specific movements without the undesirable risks associated with high head impact exposure. To this end, virtual reality equipment and software has drastically improved its availability to individual consumers, as well as to clinicians looking to improve their patient's readiness for sport. Current state of the art virtual reality systems can be purchased for a few hundred dollars with a range of software options available for sports specific and generalized training programs that address sensorimotor acuity, cognitive skills, and overall fitness. Based on the current results there is potential to employ virtual reality training strategies to augment traditional training methods, especially for those who are not physically prepared or rehabilitated to a point that they would be safe to be exposed to full contact sports

Conclusion

The current work investigated the regularity of movement patterns from young athletes performing both a realistic VR soccer header task and a standard DVJ assessment. The purpose of this work was to determine if specialized and non-specialized athletes exhibited differences in movement regularity during performance of those tasks. The results confirmed that the COG trajectories of specialized and non-specialized athletes differed with respect to movement variability as assessed by the SampEn metric. This pattern of results indicates that realistic, sport-specific VR assessments may be uniquely beneficial to expose overly rigid movement patterns of individuals who engage in repeated sport specialized practice. Further, since only the VR task was able to expose these movement differences in athletes, future considerations are warranted relative to standardized laboratory tasks and possibly the need for enhanced ecological validity in athlete assessments of injury risk. Training programs and rehabilitation, also, should include tools and techniques that maximize the variety and realism of athletic movements. Where possible newly affordable and accessible VR technology should be applied to ensure that at-risk and developing athletes are able to manage the dangers of physical contact while continuing to develop sport-related sensorimotor skills.

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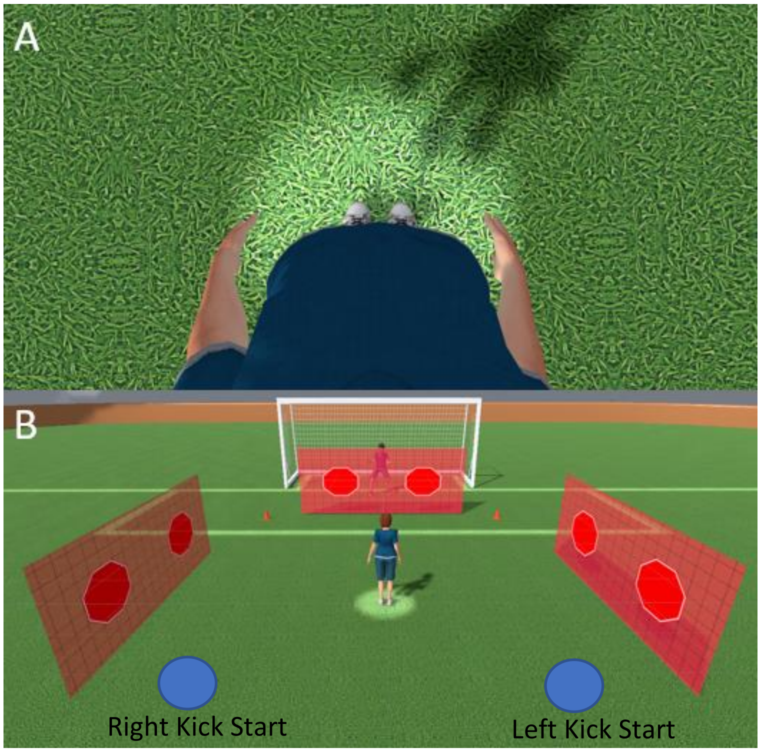

Figure 1: (a) The first person perspective of the participant's avatar and (b) the virtual boundaries that prevent a participant from approaching the laboratory walls and the starting positions for each header.

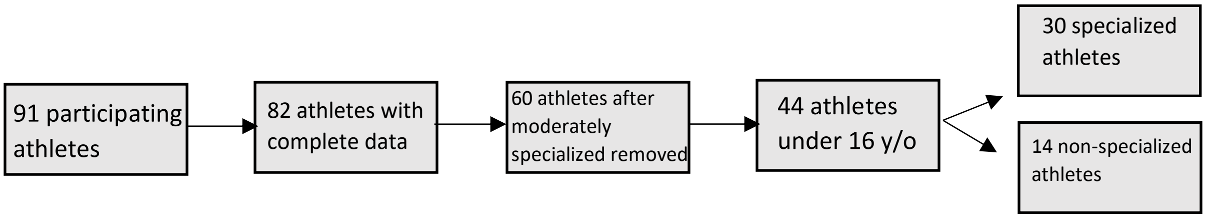

Figure 2: Diagram of participant removals due to incomplete data, specialization and age.

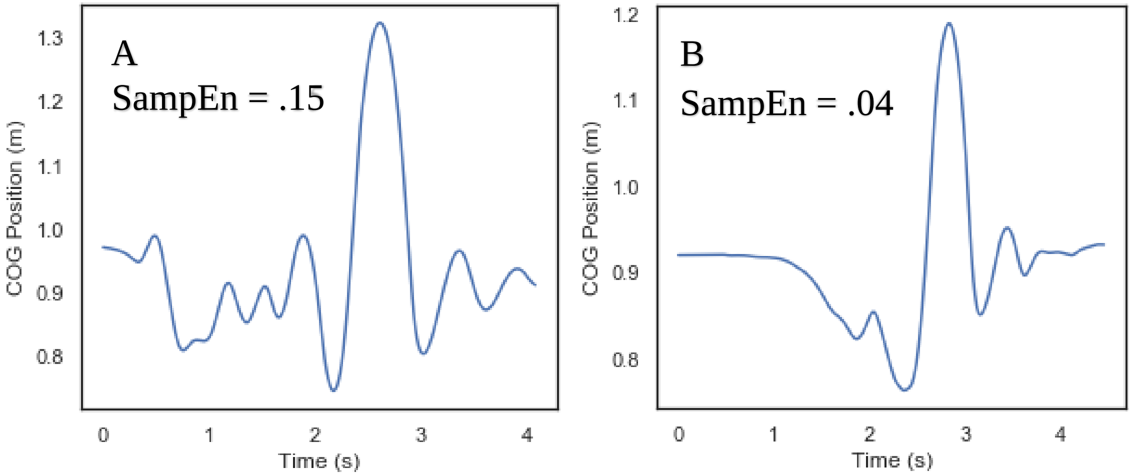

Figure 3: *Example COG trajectories demonstrating relative high (a) and low (b) sample entropy trials for the header task. These examples were drawn from non-specialized and specialized individuals respectively.*

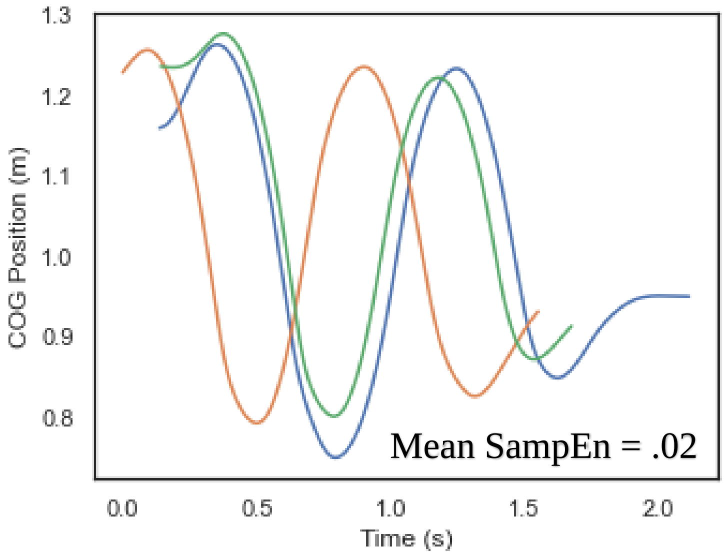

Figure 4: *Three example COG trajectories from a single participant's DVJ trials*.