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# TABLE OF CONTENTS

**Review**

1. Application of Video-Based Methods for Competitive Swimming Analysis: A Systematic Review  
   - Robert Mooney, Gavin Corley, Alan Godfrey, Conor Osborn, Leo R. Quinlan* and Gearoid O’Laighin  
   133-150

2. A Proposal for Functional Screening of the Throwing Kinetic Chain in Baseball Pitchers to Assess Shoulder and Elbow Injury Risk  
   - Shawn Cole, PT, DPT, Tom Sanderson, PT, Brian McNeill, PT, DPT, OCS and Jonathan C. Sum, PT, DPT, OCS, SCS*  
   151-158

**Brief Book Review**

   - Kimberly Outlaw, Lei Xu, Tracy Carpenter-Aeby, Victor G. Aeby* and Wenhua Lu  
   159-160

**Opinion**

4. Defining Different Types of Interval Training: Do we need to use more specific terminology?  
   - Jason L. Talanian*  
   161-163

**Short Communication**

5. Retrospective Designs in Sports Injury Surveillance Studies: All is not Lost  
   - Swarup Mukherjee*  
   164-166
Application of Video-Based Methods for Competitive Swimming Analysis: A Systematic Review

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ABSTRACT

This paper explores the application of video-based methods for the analysis of competitive swimming performance. A systematic search of the existing literature was conducted using the following keywords: swim*, performance, analysis, quantitative, qualitative, camera, video on studies published in the last five years, in the electronic databases ISI Web of Knowledge, PubMed, Science Direct, Scopus and SPORT discus. Of the 384 number of records initially identified, 30 articles were fully reviewed and their outcome measures were analysed and categorised according to (i) the processes involved, (ii) the application of video for technical analysis of swimming performance and (iii) emerging advances in video technology. Results showed that video is one of the most common methods used to gather data for analysing performance in swimming. The process of using video in aquatic settings is complex, with little consensus amongst coaches regarding a best-practice approach, potentially hindering usage and effectiveness. Different methodologies were assessed and recommendations for coaches, sport scientists and clinicians are provided. Video is an extremely versatile tool. In addition to providing a visual record, it can be used for qualitative and quantitative analysis and is used in both training and competition settings. Cameras can be positioned to gather images both above and below the water. Ongoing advances in automation of video processing techniques and the integration of video with other analysis tools suggest that video analysis will continue to remain central to the preparation of elite swimmers.

KEYWORDS: Swimming; Video analysis; Coaching; Biomechanics; Qualitative; Quantitative.


INTRODUCTION

Elite sporting success is achieved through gradual improvements over an extended period of time, to ensure that the athlete has achieved a sufficient level of physical conditioning and technical expertise. Central to this process is a detailed training plan which is prepared by the coach and monitored using a variety of means, with video-based analysis arguably the most common methodology employed in elite sport. Unsurprisingly therefore, many reviews have been published on the various applications of video in sport, including technical recommenda-
There are various methods by which video analysis is applied in different sports. A recent review of the development of video technology in coaching settings examined key questions about why and how sports coaches apply video-based methods. That author proposed that the main reason why video is used is to provide an objective record of performance, providing evidence that can be reviewed and analysed. To further understand the application of video in particular situations, reviews have been carried out for specific sports such as soccer, tennis and golf. Video analysis has been used for various purposes, including tactical; technical; physical and mental applications in different sports.

The use of video in competitive swimming is widespread, with close to three quarters of coaches based in the United States using video on a monthly basis. This is not unexpected as underwater video cameras can be positioned in ways that can record what the coach cannot see from the pool deck, thus providing him/her with additional insight into the athletes’ performances. This is essential to ensure that swimmers develop a good technique, not just for performance gains but also to reduce the risk of injury. Previous research has shown that video is used by swimming coaches mainly as a qualitative tool. This is intuitive as the qualitative process is more straightforward to implement in applied settings compared with quantitative practices. However, Lees has argued that there is a lack of information regarding the specific qualitative methods used in elite sport and also a shortage of evidence of how successful this approach may be. In a swimming context, this appears to be valid, with a dearth of published research papers outlining the application of qualitative video analysis and providing evidence of the effectiveness of the approach.

Video is also widely utilised for quantitative purposes in swimming for various applications including assessing technique, for race analysis; as a teaching tool; or as part of a medical screening process. Additionally, video is the primary means by which data for swimming research are collected and has allowed researchers to greatly advance our understanding of the mechanics governing each of the four competitive swimming strokes. Callaway, Cobb, and Jones reviewed how our understanding of swimming mechanics has developed through video analysis, focusing on research breakthroughs and making comparisons with newer sensor based technologies. Others have provided an extensive examination of the technical aspects of underwater videography, with an emphasis on calibration and reconstruction procedures.

No review has been published specifically assessing the processes by which video is captured in applied swimming settings. This may result in uncertainty amongst coaches and practitioners regarding the most appropriate methodologies to be adopted and the value of video in swimming. Additionally, it is the view of the authors that such a review could serve to provide recommendations for coaches, sports scientists and clinicians, given the challenges of working in an aquatic environment. This may lead to increased consistency in approaches to video analysis in competitive swimming to ensure the efficiency and effectiveness of coaching practices is maximized. The aim of this paper is to systematically review the applications of video-based systems for the analysis of competitive swimming. The review will focus on the processes involved in video analysis in competitive swimming; the interpretation and feedback of data for technical analysis; and will outline future developments currently emerging in the literature.

METHODS

A systematic review of the available literature on the application of video-based methods for the analysis of competitive swimming performance was conducted according to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines in an attempt to address the following review questions: (1) what are the processes involved in obtaining video-based data for swimming analysis, (2) how can the video footage be interpreted and presented for technical analysis of swimming performance and (3) what are the emerging advances in video-based technology for competitive swimming analysis. The electronic databases ISI Web of Knowledge, PubMed, Science Direct, Scopus and SPORTDiscus were searched for relevant publications over a five year period to the end of June 2015, using the following keyword search string: (swim OR swimming OR swimmer) AND (performance OR analysis OR quantitative OR qualitative) AND (camera OR video). The inclusion criteria for these articles were: (1) that they provided sufficient detail regarding the equipment specifications and experimental setup; (2) that they include relevant data regarding the application of video based methods for the analysis of competitive swimming performance; (3) that they were published in the last five years (1st July 2010-1st July 2015) and (4) that they were written in the English language. Studies were excluded if they: (1) did not involve human competitive swimmers; (2) did not provide sufficient detail to answer at least one of the review questions and (3) were published as part of conference proceedings.

RESULTS

The outcomes of the systematic search strategy process is summarised in Figure 1. The initial search identified 384 records. Reference manager software (EndNote X5, Thomson Reuters, Philadelphia, PA, USA) was used to collate results. Duplicates were removed and a screening process of both the title and abstract of the remaining records was subsequently conducted. The full-text of the remaining records was then assessed for relevance to the review. Following this procedure, 30 articles remained for the systematic review (Table 1).
Figure 1: Flowchart of the systematic literature search.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Purpose of Study</th>
<th>Exp. Design</th>
<th>No. of cameras</th>
<th>Camera config.</th>
<th>Plane(s) of movement</th>
<th>Enclosures (for UW camera)</th>
<th>Frame rate</th>
<th>No. of anatomical landmarks</th>
<th>Camera positioning</th>
<th>Variables measured using video</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>Quantify shoulder kinematics in backstroke and compare between advanced and intermediate level swimmers</td>
<td>2D</td>
<td>1AW</td>
<td>Static</td>
<td>Frontal</td>
<td>Viewing window</td>
<td>50 Hz</td>
<td>4</td>
<td>2.3 m above water</td>
<td>Shoulder entry angles</td>
</tr>
<tr>
<td>25</td>
<td>Analysis of freestyle kinematics using a markerless system</td>
<td>3D</td>
<td>6UW</td>
<td>Static</td>
<td>Sagittal, frontal</td>
<td>Waterproof housing</td>
<td>Unrep.</td>
<td>0</td>
<td>0.0-1.65 m depth</td>
<td>Shoulder, elbow &amp; wrist joint angles</td>
</tr>
<tr>
<td>26</td>
<td>Examination of the effect of breathing patterns on freestyle swimming kinematics</td>
<td>3D</td>
<td>4UW 2AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Waterproof housing</td>
<td>50 Hz</td>
<td>19</td>
<td>UW: 8 m from swimmer, 0.5 - 1.8 m depth, 75-110° optical axis AW: 12 m from swimmer, 100 ° optical axis FoV: 6.5 m per camera</td>
<td>Shoulder &amp; hip roll</td>
</tr>
<tr>
<td>27</td>
<td>Effect of fatigue on kinematics of butterfly swimming</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Waterproof housing</td>
<td>50 Hz</td>
<td>13</td>
<td>UW: 1.6 m depth AW: 0.9 m above water 2.1 x 3.0 calibration space 9 m from plane of movement</td>
<td>Velocity, stroke length, stroke rate, intra-cyclic velocity variation, stroke duration, hand &amp; foot displacement</td>
</tr>
<tr>
<td>Reference</td>
<td>Purpose of Study</td>
<td>Exp. Design</td>
<td>No. of cameras</td>
<td>Camera config.</td>
<td>Plane(s) of movement</td>
<td>Enclosures (for UW camera)</td>
<td>Frame rate</td>
<td>No. of anatomical landmarks</td>
<td>Camera positioning</td>
<td>Variables measured using video</td>
</tr>
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</tr>
<tr>
<td>28</td>
<td>Examination of the variability on arm coordination patterns in freestyle</td>
<td>3D</td>
<td>4UW 2AW</td>
<td>Static, Sagittal, frontal</td>
<td>Unrep.</td>
<td>50 Hz</td>
<td>21</td>
<td></td>
<td></td>
<td>Velocity, stroke length, stroke rate</td>
</tr>
<tr>
<td>29</td>
<td>Analyse the effect of increased energy cost on kinematics of freestyle swimming</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static, Sagittal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>0</td>
<td></td>
<td></td>
<td>Stroke rate, stroke length, velocity, arm coordination, energy cost</td>
</tr>
<tr>
<td>30</td>
<td>Analysis of kinematic differences in freestyle performance between sprint and distance swimmers</td>
<td>3D</td>
<td>4UW 2AW</td>
<td>Static, Sagittal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>19</td>
<td></td>
<td></td>
<td>Average velocity, stroke length, stroke rate, stroke duration, arm &amp; foot displacement, shoulder, elbow &amp; hip joint angles</td>
</tr>
<tr>
<td>31</td>
<td>Qualitative analysis of breaststroke technique</td>
<td>2D</td>
<td>1UW</td>
<td>Static, Sagittal</td>
<td>Viewing window</td>
<td>25 Hz</td>
<td>0</td>
<td></td>
<td></td>
<td>Water displacement due to kicking patterns</td>
</tr>
<tr>
<td>32</td>
<td>Kinematic and kinetic analysis of tumble turn performance</td>
<td>3D</td>
<td>5UW</td>
<td>Static, Sagittal, transverse</td>
<td>Water-proof housing</td>
<td>50Hz 17</td>
<td>0.7-2.0 m depth</td>
<td>45-60° optical axis</td>
<td>Temporal, kinematic &amp; kinetic parameters related to turn performance (integrated with force platform)</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Effect of starting block setup on the kinematics of track start performance</td>
<td>2D</td>
<td>1AW</td>
<td>Static, Sagittal</td>
<td>Ni/A</td>
<td>125 Hz</td>
<td>14</td>
<td>2 m from plane of motion</td>
<td></td>
<td>Block time, velocity (horizontal, vertical, resultant), flight distance, take off angle, rear foot take off time</td>
</tr>
<tr>
<td>34</td>
<td>Comparison of different feedback methods on glide performance</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static, Sagittal, frontal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>5</td>
<td></td>
<td></td>
<td>Initial &amp; average velocity, glide factor</td>
</tr>
<tr>
<td>35</td>
<td>Investigation of individual variations in limb coordination patterns</td>
<td>2D</td>
<td>2UW 1AW</td>
<td>Static, trolley, Sagittal, frontal</td>
<td>Water-proofed camera</td>
<td>50 Hz</td>
<td>0</td>
<td></td>
<td></td>
<td>Average speed, stroke length, stroke rate, IdC</td>
</tr>
<tr>
<td>36</td>
<td>Kinematical analyses of arm motion in freestyle using CAST technique</td>
<td>3D</td>
<td>6UW</td>
<td>Static, Sagittal, frontal</td>
<td>Water-proof housing</td>
<td>Unrep. 31</td>
<td>0.0-1.65 m depth</td>
<td></td>
<td>Shoulder &amp; elbow joint angles</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Comparison of different backstroke starting techniques</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static, Sagittal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>13</td>
<td></td>
<td></td>
<td>Centre of mass position and velocity, contact time, take off angle, back angle arc, flight distance, start time</td>
</tr>
<tr>
<td>38</td>
<td>Effect of resistance on propulsive forces during freestyle sprint swimming</td>
<td>3D</td>
<td>4UW</td>
<td>Static, Sagittal</td>
<td>Periscope</td>
<td>60 Hz</td>
<td>11</td>
<td>3 x 1 x 1 m³ capture volume</td>
<td></td>
<td>Pitch &amp; sweepback angles, hand velocity, propulsive forces</td>
</tr>
<tr>
<td>39</td>
<td>Characterization of backstroke swimming kinematics at high intensity</td>
<td>2D</td>
<td>2UW</td>
<td>Static, Sagittal, frontal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>12</td>
<td></td>
<td></td>
<td>Average velocity, stroke rate, stroke length, stroke index, IdC</td>
</tr>
<tr>
<td>40</td>
<td>Investigation of correlation between technique with velocity profile in breaststroke swimming</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Trolley, Sagittal</td>
<td>Water-proofed camera</td>
<td>50 Hz</td>
<td>0</td>
<td></td>
<td></td>
<td>Stroke phase analysis (arms &amp; legs), stroke rate, stroke length, IdC, speed</td>
</tr>
<tr>
<td>Reference</td>
<td>Purpose of Study</td>
<td>Exp. Design</td>
<td>No. of cameras</td>
<td>Camera config.</td>
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<td>No. of anatomical landmarks</td>
<td>Camera positioning</td>
<td>Variables measured using video</td>
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</tr>
<tr>
<td>41</td>
<td>Analysis of the kinematics of backstroke turns</td>
<td>2D</td>
<td>4AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>N/A</td>
<td>25 Hz</td>
<td>0</td>
<td>All cameras positioned 7 m above and 7 m away from pool 2 cameras fixed at ends of pool, perpendicular to plane of motion, 2 cameras fixed with optical axes crossed (one from 0.15 m and the other from 10-25 m)</td>
<td>Turn time (7.5m round trip), distance in, UW distance, velocity, normalized velocity, stroke velocity</td>
</tr>
<tr>
<td>42</td>
<td>Examination of dolphin kicking performance</td>
<td>2D</td>
<td>1UW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Water-proof camera</td>
<td>30 Hz</td>
<td>12</td>
<td>0.5 m depth, 7.5 m from push-off wall, 4 m from swimmers plane of motion</td>
<td>Kick symmetry, displacement, amplitude &amp; frequency. Horizontal centre of mass velocity, relative angles for ankle, knee, hip, shoulder, elbow, wrist, upper waist, lower waist &amp; chest.</td>
</tr>
<tr>
<td>43</td>
<td>Examination of the pitching effects of buoyancy using a markerless system</td>
<td>2D</td>
<td>2UW 1AW</td>
<td>Trolley, towing cable</td>
<td>Sagittal, transverse</td>
<td>Unrep.</td>
<td>50 Hz</td>
<td>0</td>
<td>Unrep.</td>
<td>Centre of mass &amp; centre of buoyancy positions, buoyancy torques, moment of inertia</td>
</tr>
<tr>
<td>44</td>
<td>Effect of breathing patterns on freestyle swimming kinematics</td>
<td>2D</td>
<td>1AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>N?A</td>
<td>50 Hz</td>
<td>2</td>
<td>2.35 m above water Approx. 11.7 m from swimmer FoV: 7.5 m</td>
<td>Stroke rate, stroke length, velocity</td>
</tr>
<tr>
<td>45</td>
<td>Assess the effect of leg kicking dynamics on freestyle kinematics</td>
<td>3D</td>
<td>4UW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Periscope</td>
<td>60 Hz</td>
<td>6</td>
<td>3 x 1 x 1 m² capture volume</td>
<td>Stroke rate, stroke length, velocity, intra-cyclical hip velocity, iDC, pitch &amp; sweepback angles</td>
</tr>
<tr>
<td>46</td>
<td>Determine the accuracy of a 3D kinematics system for swimming analysis</td>
<td>3D</td>
<td>8AW</td>
<td>Static</td>
<td>Sagittal, frontal</td>
<td>Viewing window</td>
<td>200 Hz</td>
<td>4</td>
<td>0.55-2.0 m height 1.4-1.9 m from viewing window 0.45-1.8 m between cameras</td>
<td>Sweepback &amp; pitch angles</td>
</tr>
<tr>
<td>47</td>
<td>Effect of aerobic training on freestyle kinematics</td>
<td>2D</td>
<td>2UW 1AW</td>
<td>Static &amp; panning</td>
<td>Sagittal, frontal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>0</td>
<td>UW: panning camera positioned at mid-pool, static camera captured frontal plane AW: profile view of entire swim trial</td>
<td>Stroke rate, stroke length, velocity, iDC, propulsive phase duration</td>
</tr>
<tr>
<td>48</td>
<td>Examination of the kinematics of the backstroke start technique</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Viewing window</td>
<td>60 Hz</td>
<td>14</td>
<td>UW: 1.5m depth AW: 9.2m above water 7.5 m from plane of motion</td>
<td>Hip &amp; knee joint angles, angular velocity, hip &amp; toe displacement, time to 5m</td>
</tr>
<tr>
<td>49</td>
<td>Assessing the relationship between coordination and energy cost of freestyle and breaststroke swimming</td>
<td>2D</td>
<td>2UW</td>
<td>Static</td>
<td>Sagittal, frontal</td>
<td>Unrep.</td>
<td>50 Hz</td>
<td>0</td>
<td>FoV: 10 m, between 10 &amp; 20 m mark in 50 m pool</td>
<td>Average velocity, stroke rate, stroke length, iDC, stroke phases, kick rate, arm &amp; leg coordination</td>
</tr>
<tr>
<td>50</td>
<td>Analysis of kinematic parameters relevant to starts and turns, comparing national and regional level swimmers</td>
<td>2D</td>
<td>2AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>N/A</td>
<td>25 Hz</td>
<td>0</td>
<td>Cameras positioned 7 m above and 7 m away from pool</td>
<td>Turn distance &amp; velocity, start distance &amp; velocity</td>
</tr>
</tbody>
</table>
Table 1: Results of systematic review search summarising studies conducted that apply video-based systems for the analysis of swimming performance. Results are presented in chronological order and include the purpose of the study; experimental and equipment details; the number of anatomical landmarks and the variables that were measured using the video footage. Abbreviations: UW: Underwater; AW: Above Water; FoV: Field of View; Unrep: Unreported; IdC: Index of coordination.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Purpose of Study</th>
<th>Exp. Design</th>
<th>No. of cameras</th>
<th>Camera config.</th>
<th>Plane(s) of movement</th>
<th>Enclosures (for UW camera)</th>
<th>Frame rate</th>
<th>No. of anatomical landmarks</th>
<th>Camera positioning</th>
<th>Variables measured using video</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>Examination of the impact of verbal feedback on technique</td>
<td>2D</td>
<td>1UW 1AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>Water-proofed camera</td>
<td>50 Hz</td>
<td>3</td>
<td>Cameras fixed mid-pool</td>
<td>Stroke rate, stroke length, velocity</td>
</tr>
<tr>
<td>52</td>
<td>Investigation of path linearity in elite freestyle swimmers</td>
<td>2D</td>
<td>2AW</td>
<td>Static</td>
<td>Sagittal</td>
<td>N/A</td>
<td>50 Hz</td>
<td>0</td>
<td>6 m above water 15 m from plane of motion</td>
<td>Forward &amp; lateral speed fluctuations</td>
</tr>
<tr>
<td>53</td>
<td>Examination of the effect of swim speed on coordination in Paralympic swimmers</td>
<td>2D</td>
<td>2UW</td>
<td>Trolley</td>
<td>Sagittal</td>
<td>Water-proof housing</td>
<td>50 Hz</td>
<td>4</td>
<td>6.5 m from swimmer (left and right sides), FoV included whole body of participants, 10 m test window</td>
<td>Arm and leg cycle phases, swim speed, stroke frequency, kick frequency, kick pattern, downbeat time, upbeat time, pull time, recovery time, leg to arm coordination</td>
</tr>
</tbody>
</table>

DISCUSSION

Process of Video Capture

It has been found that technical examination of a swimmer in an applied setting can be undertaken using many different types of video setup and using various analysis methods (Table 1). For example, quantitative or semi-quantitative techniques involve an objective, deductive means of examining components of a performance using specialized instrumentation. Alternatively, a qualitative approach is more inductive in design and analysis is descriptive and subjective in nature. Qualitative analysis can be carried out to assess the quality of the performance or technique but is also important as a method of identifying the key variables that need to be measured by quantitative means at a later stage. Figure 2 provides an overview of the video analysis process. Three stages are involved: (i) camera selection and setup (ii) video capture and (iii) data processing and analysis. Following these three stages, a coach will interpret the results, provide feedback to the swimmer and decide on appropriate intervention strategies.

Camera Selection and Setup

Equipment specifications: Swimming presents unique challenges to the application of video that warrant consideration. Important issues to consider include light refraction and the effect of water turbulence such as bubbles and splash that are generated by a swimmers movements. Refraction can result in the distortion of an image when light passes from a fast medium (air) to a slow medium (water). An additional concern for underwater recording is water clarity and its effect on image quality. For example, a swimming pool that is excessively aerated will result in high levels of bubbles around the swimmer, making identification of anatomical landmarks on the swimmer difficult (Figure 3).

Figure 2: The process of video capture for swimming analysis involves three stages: (i) camera selection and setup; (ii) video capture and (iii) data processing and analysis. This may be conducted in either training or competition settings.

Figure 3: The motion of a swimmer in the water can cause turbulence resulting in bubbles that make identification of landmarks difficult. Rapidly moving body segments can also result in a blurred image.
There is a vast array of video cameras to choose from, with both underwater and above-water cameras available from all the major camera manufacturers. Studies that utilise only above-water cameras tend to be analyses based on competition footage. However, for a thorough technical examination of swimming using video it is imperative for the swim coach to have an underwater view to fully assess a swimmer’s movements. Specialist underwater equipment is available through dedicated manufacturers. Examples include SwimPro, SwimRight and Qualisys Oqus (Table 2). Some key parameters to consider when choosing a camera include the frame rate and shutter speed. Frame rate refers to the number of individual frames that comprise each second of video, also known as FPS (frames per second). Shutter speed refers to the amount of time that each individual frame is exposed for. It is generally advised that the denominator of your shutter speed should be at least double the number of FPS that you are recording. Consequently, a frame rate of between 25-50 Hz and a shutter speed of between 1/350-1/750 s are recommended for swimming applications to maximise image quality. These frame rates are reflected in the extant literature although some examples of higher values such as 125 Hz and 200 Hz can be found.

Various solutions have been developed to record underwater motion, including placing the camera in a waterproof housing; using an underwater viewing window or alternatively a periscope system (Figure 4). Although periscope systems were frequently used in the past, waterproof camera housings appear to now be the most popular choice and offer flexibility in positioning but have short camera to interface distances (the distance between the camera lens and the glass of the waterproof housing) which can result in reconstruction errors (Figure 5). Underwater viewing windows allow for increased camera to interface distances but video capture will be limited by access to a swimming pool or flume with built in windows included and may also result in issues with refraction. Inverse periscopes allow for camera’s to be positioned above the water to record activity both above and under the water. The advantage of a periscope system is that it allows for a longer camera to interface distance compared to waterproofed camera housings. However, the mirrors used in periscope systems must be of a very high quality to ensure good image quality and consequently periscope systems can be expensive compared with the alternative approaches.

<table>
<thead>
<tr>
<th>Camera System</th>
<th>Shutter Speed (s)</th>
<th>Frames per second (fps)</th>
<th>No. of Cameras</th>
<th>Resolution (Mpixel)</th>
<th>Min Illumination (Lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SwimRight Shark Eye</td>
<td>1/50-1/10,000</td>
<td>25-30</td>
<td>1</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>Coach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SwimPro IQ Rec</td>
<td>1/50-1/60,000</td>
<td>1-4</td>
<td>1</td>
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<tr>
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<td>12-240</td>
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</tr>
<tr>
<td>Qualisys Oqus</td>
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<td>180-10,000</td>
<td>1-24</td>
<td>0.3-12.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 2: Comparison of technical specifications for various underwater cameras systems used in competitive swimming environments, highlighting that no common configuration has been established.

Figure 4: To capture the underwater movements of the swimmer different options are available for the positioning of cameras including (a) using a waterproof housings such as the Shark Eye system; (b) a periscope system or (c) placing cameras outside the water and tracking the swimmers as they pass underwater viewing windows. Redrawn from Yanai et al. (1998) and Reproduced from Monnet et al. (2014) (Figure 4B) and Reproduced from Monnet et al. (2014) (Figure 4C), with permission.

Figure 5: When using a waterproof housing, the distance between the camera lens and the glass of the housing is important as refraction at both the water-glass interface and glass-air interface will cause deformation of the image. The thickness of the glass will also affect the degree of refraction experienced.
Camera Configuration

Using a single camera offers an ease of portability and setup, and can often be used for a rapid performance assessment. Use of multiple cameras requires a more complex setup and requires images from different cameras to be synchronized. Between one and eight cameras have been used in studies capturing swimming footage, with various combinations of above-water and under-water cameras. Cameras can be positioned to capture the swimmer in the sagittal, transverse or frontal planes, or a combination of these, depending on the analysis requirements.

Payton recommended that the size of the athlete in view be maximized in order to reduce perspective error. Perspective error results in the size of an object changing with its distance from the lens and overcoming this is critical in measurement applications involving objects with depth or objects moving relative to the lens. This can be achieved through a combination of increasing the distance from the camera to the performer and choosing an appropriate zoom level. Whilst this is seldom an issue for above water cameras, when recording underwater this can present a challenge as it can often require several lanes of the pool to be left empty to avoid other swimmers from blocking the view. Moreover, underwater lenses have a fixed focal length (the distance between the centre of the lens and its focus). And do not allow for adjustment in zoom or shutter speeds so it is necessary to increase the distance of the camera position in relation to the swimmer, which may be impractical for many training programmes.

Static cameras are typically used in order to allow for the movement to be assessed relative to an external reference. The camera is fixed on a specific field of view and...
the footage is captured as the swimmer moves past. When using a smaller capture space, issues arise as only a short number of stroke cycles can actually be recorded within the capture space. This may limit the effectiveness of such an approach as it does not allow for variations in swimmers patterns of movement to be fully observed.62,63

Panning cameras introduce additional complexity for accurate measurement but can be used to capture a swimmer’s movements through a longer distance, for example over the full length of an Olympic distance pool.58 Alternatively, tracking cameras allow the videographer to manually follow the swimmer throughout the length of the pool using a camera mounted on a trolley or similar device.56,63 This increases the analysis potential beyond the limited capture volume possible with static cameras.

**Calibration procedures:** Calibration of a video image for a 2D quantitative analysis requires a scaling object and vertical reference to be recorded before video capture, to facilitate accurate extraction of variables during the digitization stage.1 Typically, this is achieved using a metre stick. When conducting 3D analysis, a controlled volume is defined according to a calibration frame of known dimensions with control points positioned at known intervals and the calibration frame design must reflect its intended use.

Examples of differently sized calibration frames used in swimming can be found in the literature. Larger frames are capable of capturing the entire swimmer during one or more stroke cycles, with examples as large as 18 m³ and 25.2 m³ previously described. Others have used a calibration frame with dimensions of 4.5 m x 1.0 m x 1.5 m (6.75 m³) which is also suitable for whole body analysis.38 Cappaert, Pease, and Troup64 used a 5.6 m³ calibration frame in a whole body swimming investigation. These researchers used digitized footage from four cameras (two below and two above the water) to determine changes in shoulder, hip and elbow angles throughout one stroke cycle, to compare the techniques of elite and sub-elite swimmers.

Conversely, smaller calibration frame sizes have also been utilized.38,55-57,65 Payton, et al.57 used a frame measuring 1.3 m x 0.93 m x 0.88 m (1.06 m³) and digitized six anatomical landmarks on the shoulder, forearm and hand in order to determine the movements of one arm during a single stroke. Lauder, et al.65 previously reported the smallest frame found in a swimming related study, measuring just 0.4 m³ (1.0 m x 0.5 m x 0.8 m). These studies focused on specific aspects of swimmer’s arm movements and the relationship of these with propulsion. Smaller frame sizes can result in lower reconstruction errors than larger frames.57 These reconstruction error differences be attributed to various factors, including the effects of light refraction; image deformation when recording; the relative size of the reproduced image in relation to the capture volume or issues with the reconstruction algorithms used.22,35 A trade off exists in deciding the appropriate calibration frame size and the resultant accuracy of the reproduced image. Additionally, the frame size can be compensated for somewhat by increasing the distance between the camera and the performer.

**Video Capture**

**Preparation of swimmers:** There are various factors involved in preparing swimmers for video-based data collection. Some factors are common to both quantitative and qualitative analysis, but quantitative methods will require additional preparation. Swimmers may be required to wear specific clothing (such as different coloured hats or swim-suits to aid identification), have identification markers written on their skin, or some other markers for identifying body landmarks when conducting digitization procedures (Figure 7). Digitization involves the reconstruction of a swimmers body movement by tracking the displacement of markers placed at specific anatomical locations. Up to 31 landmarks have been included in the reviewed literature,36 although the number of specific locations of the markers will depend on the aims of the study. It is important to note that the swimmer cannot typically hear or see the videographer whilst performing trials so it is vital that instructions regarding the protocol are clearly communicated to the swimmer in advance to improve the efficiency and accuracy of data collection.

![Figure 7: Representation of the anatomical locations of body segments used to facilitate the digitization process for kinematic analysis. The accuracy of the digitization process is dependent on anatomical knowledge when markings are made. Reproduced from Atkinson et al. (2013), with permission.](image-url)
Video storage and retrieval: Various software packages are available, including Dartfish; Kinovea; Quintic; APAS; Coaches Eye and Simi Motion, for video capture, editing and subsequent analysis. Video requires a large amount of storage space on a computer, with footage of a typical 200 m race lasting 2-3 minutes taking up 250-300 MB. Recordings taken during a training activity are typically longer in duration and require much larger storage space.

A large volume of recording raises two concerns for the coach. Firstly, a suitable storage solution must be available with sufficient capacity for dealing with multiple recordings over an extended period of time. This may involve a physical hard drive or a cloud based solution. Advances in cloud based computing allow for vast storage and sharing solutions for coaches but this may also involve a lot of time for compressing, uploading and downloading of information when large squads of swimmers are involved. Secondly, a coach must have a system that allows for rapid retrieval of information at a later stage. This may involve manually indexing and tagging data, to attribute information related to a specific swimmer, event or analysis type conducted. Many software packages will include features for this to be carried out or alternatively a coach may develop their own notational system. It is important that coaches and sports scientists working with the same group of swimmers follow a consistent approach for ease of retrieval at a later stage.

Data Processing and Analysis

For a qualitative analysis, it is typically only necessary to edit and store the files for later review. However, processing may involve merging of images from multiple views for thorough assessment. Data processing for quantitative analysis involves additional steps however. Digitization procedures are required to obtain the coordinates of body landmarks from recorded video and can be completed using manual or automatic methods. Manual methods involve an operator having to identify landmarks through visual inspection of each frame of the footage. In order to improve the consistency of the process, the same operator should perform all the digitizing for data to be analysed. Certain limb positions can be difficult to identify due to water turbulence or hidden body segments. Operators should have a sound anatomical knowledge and use markers on the skin only as a guide.

The scaling object or control points must be digitized with a high degree of accuracy as this process is used to generate all other outputs from the system. It is also recommended to assess the level of systematic and random error involved. Errors can arise from various factors including the quality of the video image; the resolution of the digitization software; the size of the calibration volume and the skill of the operator. Error estimation typically involves a both inter-operator and intra-operator reliability testing. Reconstruction error for 3D analysis of less than 5 mm for each axis is deemed acceptable.

According to swim coaches, a key disadvantage to performing quantitative video analysis methods is the time taken to manually digitize the footage. Coaches perceive that it takes too long to carry out quantitative analysis and this outweighs any perceived advantage of conducting such work. A recent study reported that it took approximately seven and a half hours to carry out manual digitization of a relatively small amount of footage, involving ten swimmers performing three dives each. Megalhaes, et al. also cite another example whereby it took 27 hours to digitize footage of four separate stroke cycles for one swimmer, involving images from six cameras, 19 anatomical landmarks and 1,620 frames in total.

Automatic digitization offers a clear time-saving advantage over manual methods. However, it is not always possible to complete automatic digitization as markers cannot always be placed on a performer (in a competitive setting for example) and in the water the negative drag effects of markers hinders the swimmers movements significantly. An increase of between 7%-10% in passive drag was reported in one study which involved 24 markers, each 19mm in diameter. Additionally, underwater and/or outdoor conditions lead to variations in the pixel contrast (the difference in luminance or colour that makes an object or its image representation distinguishable) between the markers and the background and air bubbles in the water can also introduce additional error in automatic procedures, rendering them impractical.

Based on the evidence presented in this review, the overall trend in video capture in swimming appears to be towards the use of multiple cameras and that both the underwater and above water images are important to the coach. This is logical as it allows for swimmers movements to be tracked through complete stroke cycles and from multiple planes of motion. Increased availability of low-cost equipment is also facilitating coaches in obtaining these multiple views. Additionally, whilst many 3D analysis setups are found in research practice, there is a much greater emphasis on 2D approaches, especially in applied practice.

INTERPRETATION AND FEEDBACK

Qualitative Technical Assessment

Commonly, a coach will conduct technical analysis using video as an aid to their own observations. This analysis is based on a coach’s own knowledge and experience but video allows the coach to prepare, observe, assess and evaluate a swimmer’s performance before taking what they consider to be the most appropriate action. A key advantage is that it is low cost and easy to implement with large numbers of athletes. Wilson suggests that in coaching settings there is more of a focus on qualitative analysis as it allows for rapid video feedback to be provided at any stage during a training session. Moreover, qualitative analysis is considered by some to be more intuitive for an
One recent study used a qualitative approach to assess different breaststroke techniques. By using an underwater camera, researchers were able to use flow visualization techniques to assess the impact of different arm and leg movements (Figure 8). For example, it was found that supination of the foot at the end of leg extension resulted in increased displacement of the swimmer compared with leg extension without a corresponding foot supination.

Another example of the application of video for qualitative assessment is the use of self-modelling. Self-modelling is an observational technique based on preparing a video of an athlete’s own performance that has been edited to show a performance level that is greater than what the athlete is currently capable of. Such an approach has been implemented previously for the learning of swimming skills and may also have relevance in competitive environments. This may involve taking video footage of a swimmer’s four best laps (from a longer race or from different performances) and editing them together with the swimmer’s best ever start, turns and finish, to create a video file that the swimmer can then view. This approach has been used in competitive gymnastics and shown to significantly increase performance compared to when no video is provided to the athletes.

This visual feedback on performance is vital for skill acquisition, it raises a swimmer’s awareness of their movements in the water and it is suggested that feedback should be provided as quickly as possible during the skill acquisition stage to maximise the learning effect. Furthermore, it has believed that the timing and content of feedback information should change as learning and skill development progresses. Video facilitates this augmented feedback approach just as readily.

Video allows for a thorough qualitative evaluation from any viewing angle to be conducted. As most of a swimmer’s movements occur under the water it is difficult for a coach to see what is going on. Therefore, underwater video appears to be just as important for the coach as it is for the athlete. Manipulation of the video image using tools such as slow motion replay, frame-by-frame viewing or split screen comparisons can be used to facilitate both observation and assessment of the performance and highlight issues that could be missed with the naked eye. Moreover, video footage can be used to compare the same swimmer on different occasions to check for changes in technique following a period of training or for the effects of fatigue.

The lack of qualitative swimming research highlighted in this review is of concern as it has been found that coaches most often employ qualitative procedures in their own environments. However, without a strong evidential basis for its efficacy, it is possible that coaches are not making the best use of the methods, leading to poor practice and potentially inefficient performance gains. Future research should focus on examining the merits of qualitative approaches in applied swimming settings.

Quantitative Technical Assessment

Alternatively, video may be used along with specialist equipment and software to assess swimming technique using quantitative or semi-quantitative means. Whilst qualitative analysis using video has been shown to be an effective method of producing changes in technique compared with verbal coach feedback, it has been suggested that quantitative feedback is also important for improving technique rather than using video purely for qualitative analysis. Thow, et al. reported significantly greater improvements in both initial and average velocity measurements in elite swimmers during the glide phase following a dive start when swimmers were provided with quantitative feedback to compliment the coach’s instructions. Average velocity increased from 1.74±0.16 m s⁻¹ to 1.84±0.09 m s⁻¹ over a five week intervention period. Moreover, whilst the results indicated that a qualitative feedback approach also brought about significant gains in performance, the addition of quantitative data elicited faster improvement gains.

Video facilitates the quantification of key performance-related parameters, which have been shown to significantly influence overall performance. These quantitative methods can also be applied to injury prevention strategies. Becker and Havriluk used video to assess different phases of butterfly swimming technique in order to highlight how changes to technique can re-
duce the risk of injury by affecting the forces experienced by the swimmers' hands as they propel themselves through the water. Furthermore, video has been used to determine stroke asymmetry and has informed musculoskeletal screening procedures to help clinicians and coaches to identify such deficiencies.

The studies included in this review demonstrate that video has been used in a diverse number of ways for providing analysis in swimming. Whilst some differences can be attributed to the advancement of filming and computer technology, the review does highlight an apparent lack of common approaches for conducting quantitative video analysis in swimming, with different studies using different camera configurations to measure the same variables. What is also apparent is that in-depth quantitative video analysis does not always require a complex experimental setup.

For example, the pitch and sweepback angles of the hand are important factors for generating propulsion. Recent studies have used either two, four or eight cameras positioned either in waterproof housings, behind viewing windows or with a periscope system and have digitized between 4 and 12 anatomical landmarks in order to measure these angles. Similarly, velocity, stroke rate and stroke length have been variously derived using static cameras, or cameras with a trolley setup, both with and without digitization procedures. Such diversity in approaches is undoubtedly due to the specific nature of different studies, but may lead to confusion among practitioners as to the best methods to employ in their own environments.

Turns are a vital component of swimming competition and have been shown to be significantly related to overall performance, and as a result have received much research attention. Puel, et al. provided a comprehensive three-dimensional analysis of the key parameters related to successful performance of the freestyle tumble turn, using five underwater cameras and an integrated force platform to quantify 51 separate variables. In contrast, Veiga, et al. recently also assessed turning performance in a group of elite swimmers but used just two above water cameras and measured only turning distance and velocity. Clearly the objectives of these studies differed but it is interesting to consider which study would be more likely to be replicated by a coach in their own environment.

EMERGING ADVANCES IN VIDEO TECHNOLOGY

The criticisms of video appear to be commonly expressed by both researchers and coaches. A central theme of this criticism is the time required to carry out video based procedures. This is certainly limiting the frequency of quantitative video analysis performed in applied settings but is likely to also decrease qualitative video practices, given that video editing for multiple swimmers can be very labour intensive in its own right. It is unsurprising therefore that much research attention is currently focused on reducing the time taken to obtain pertinent information using video and on the automation of many of the laborious manual procedures involved. By way of example, one recently reported automated digitization approach claims to reduce processing time by a factor of ten over manual tracking methods.

Automated Tracking Systems

One automated tracking approach uses an array of LED’s mounted on flexible circuit board that was worn by the swimmer. The system removes the requirement for manual digitization and initial testing suggests comparable accuracy to manually derived variables related to swimming starts and turns. Another automated tracking system recently described is based on the Calibrated Anatomical System Technique (CAST). The CAST system, frequently seen in clinical settings, estimates anatomical landmarks based on joint degrees of freedom and can be used to estimate the position of hidden landmarks. Initial results indicate that this approach may be suitable for swimming applications, although the procedures are still time-consuming and complex, with 31 anatomical landmarks required during swimmer preparation for one arm and a portion of the trunk to be digitized, which perhaps offsets the time gained elsewhere.

Marker-Less Analysis

Another emerging approach found in other sports is a marker-less 3D analysis method based on the extraction of a swimmer’s silhouette from video images. Marker-less systems have an advantage over other techniques for swimming applications, as form and drag caused by markers are central concerns. The results of initial investigations suggest that this method shows similar reliability to manual digitisation approaches, but further investigation of system reliability has been suggested. This method may help to reduce both participant preparation and processing time and has also been investigated in other sports to provide real-time kinematic data on performance with promising results. As with any new methodology, additional investigation will be required to fully assess the merits and feasibility of any new approach for applied settings. For instance, the system described by Ceseracciu, et al. was tested for one arm only and for front-crawl swimming, and it remains to be seen if the same level of accuracy would be achieved for whole body kinematic analysis and for other swimming strokes. This trend towards automated procedures is likely to lead to increases in quantitative analysis practices as the time constraints associated with digitization are reduced. However, it could be reasonably argued that many of the automatic video analysis procedures are currently overly costly to be applied in the majority of coaching settings, with one example costing over US $35,000 to purchase the equipment and software (ProAnalyst, Xcitex Inc., Woburn, MA, USA). Additionally, with a concurrent growth in interest in alternative methods of quantifying swimming performance, some have argued that more suitable solutions are starting to emerge, such as the use of low cost Micro-Electro-Mechanical Systems (MEMS) inertial sensor devices. What is more likely is that integrated systems will
become more prominent, with data measurements arising from multiple sources.

CONCLUSIONS AND RECOMMENDATIONS

The aim of this paper was to systematically review the process of applying video-based systems for the analysis of competitive swimming. It is clear that video can be used in a variety of ways to provide feedback, and to aid technical development and to reduce the risk of injury. Video allows a coach to review, reflect and evaluate the development of many aspects of athletic preparation and can be used to facilitate both qualitative and quantitative analysis.

Video capture in swimming shares many common characteristics with other sports, but with additional considerations for underwater filming. The aquatic environment adds to the time, cost and complexity of implementing video analysis. In using video to provide feedback to swimmers, coaches must make appropriate decisions regarding the equipment, camera configurations and processing methods involved, and ensure they follow key recommendations.

There are a large number of factors to be considered when using video analysis for swimming applications and no common specifications or methodologies appear to exist. It could be argued that this lack of consistency is hindering the effective-

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**Figure 9:** Flowchart detailing recommendations for the key steps to be followed and decisions to be made when undertaking video analysis in swimming.
ness of the technique. A more consistent approach would remove some of the confusion around the process and could facilitate increased use of video. Figure 9 provides a detailed flowchart of the various stages involved and is intended to provide recommendations that may aid decision making and perhaps improve the effectiveness of video for coaching purposes.

It would appear that the key feature of video is its adaptability to various applications. Video analysis can be tailored to suit the specific needs at the time. If rapid feedback is required, video can facilitate instant review by both the coach and the swimmer. Additionally, video can be edited, processed and reviewed either qualitatively or quantitatively to provide an augmented feedback approach. Furthermore, video can be used to capture movement in both 2D and 3D for in-depth study or combined with other measurement tools. Finally, video can also be used in training, competition and research situations, and can capture movements both above and under the water. This versatility extends its application potential far beyond other analysis systems used in elite sport. With continued advances in video and software technology it is also likely that video will continue to remain an integral part of the elite training environment in future.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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A Proposal for Functional Screening of the Throwing Kinetic Chain in Baseball Pitchers to Assess Shoulder and Elbow Injury Risk

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ABSTRACT

Overhead throwing athletes are susceptible to overuse injuries in the upper extremity, specifically of the shoulder and elbow. These injuries can include rotator cuff tears, labral tears, and ulnar collateral ligament sprains and can affect athletes at all levels of their sport. To address this growing epidemic, musculoskeletal screens and assessments are used to identify risk factors associated with injuries. Though the baseball pitching delivery has been extensively studied in biomechanical laboratories, a clear consensus agreement of the essential tests and measures is still lacking, both as a pre-participation assessment of injury risk and for return to sport criteria. Most recent research has been focused on the contributing factors of the entire kinetic chain, relating deficits in the kinetic chain to impairments seen in the upper extremity which may lead to shoulder and elbow injury. The purpose of this article is to use the essential components of the throwing kinetic chain to propose a novel screening assessment for the overhead throwing athlete, which can be used as a pre-participation assessment of injury risk or for return to sport criteria.

KEYWORDS: Elbow injury; Pitchers; UCL.

ABBREVIATIONS: UCL: Ulnar Collateral Ligament; MLB: Major League Baseball; SLAP: Superior Labrum Anterior to Posterior; GIRD: Glenohumeral Internal Rotation Deficit; TRM: Total Rotational Motion; MVIC: Maximal Voluntary Isometric Contraction; NCAA: National Collegiate Athletic Association.

INTRODUCTION

Overhead throwing athletes are at an increased risk for overuse injuries primarily of the shoulder and elbow due to the cumulative microtrauma associated with repetitive throwing. In Major League Baseball pitchers, injuries to the shoulder account for 28% of all injuries, injuries to the elbow account for 22-26%, and combined account for more missed games than injury to any other anatomical region. Injuries at the professional level appear to be on the rise. In May of 2014, Jose Fernandez of the Miami Marlins became the 18th player to undergo Tommy John surgery to repair the Ulnar Collateral Ligament (UCL) of his pitching elbow since the start of that Major League Baseball (MLB) season. This was just one shy of the total number of Tommy John surgeries performed in all of the previous season. At this rate, the 2014 season was on pace to surpass the record setting 2012 season of 36 surgeries; ultimately finishing with 29 players undergoing surgery. Shoulder and elbow injuries are present at other levels of baseball as well. A survey of 490 junior high, high school, and college baseball players with shoulder and elbow injuries found, that all elbow injuries and the majority of shoulder injuries were prevalent at the high school and college levels. Thirty-seven percent of the elbow injuries involved the UCL and 19.8% of all shoulder injuries were Superior Labrum Anterior to Posterior (SLAP) lesions.

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UCL injuries are of particular interest due in part to the significant amount of time required to return to elite level pitching following surgery. UCL reconstruction has been on the rise in high school-aged baseball players for several years. Literature suggests that year-round training and competition increases the likelihood of a youth baseball pitcher suffering a shoulder or elbow injury.\textsuperscript{6,11} The number of pitches thrown, the type of pitches thrown, and the overall physical fitness of the youth baseball pitcher can increase the risk for shoulder and elbow injuries.\textsuperscript{10,12,15} Fifteen percent of college-level pitchers consider injuries sustained playing youth baseball have limited current performance.\textsuperscript{14}

To help reduce the risk of injury in pitchers, several recommendations have been proposed, including pitch count restrictions and required rest days.\textsuperscript{13} Youth players should limit breaking balls thrown until they have passed the developmental stages of puberty.\textsuperscript{12,15} Finally, throwing athletes should undergo biomechanical assessment encompassing whole body screening. This would ensure all aspects of the kinetic chain have the mobility and stability required to safely and effectively throw without increased risk for injury.\textsuperscript{16,17}

With shoulder angular velocities exceeding 7250° sec\textsuperscript{-1} and varus torques at the elbow of nearly 100 Nm any weakness, tightness, or lack of neuromuscular control of the body can cause subtle changes in the pitching motion.\textsuperscript{6,7} These subtle changes in the pitching motion can alter the kinetic chain, which may increase physical stresses on other anatomical areas such as the elbow and shoulder. Over time these changes can lead to tissue failure and injury.\textsuperscript{1} Being able to effectively and efficiently screen for individuals that have kinetic chain deficits may help to identify individuals who are at an increased risk for injury and allow the athlete to receive proper training, conditioning, and intervention to prevent injury. The purpose of this article is to propose a novel screening assessment for the overhead throwing athlete using the essential components of the throwing kinetic chain, which can be used as a pre-participation assessment of injury risk or for return to sport criteria.

**BACKGROUND**

Overhead throwing is a movement that is not isolated to the shoulder and elbow. It is a complex interaction of total body strength, range of motion, static and dynamic balance, proprioception, and neuromuscular coordination. All of these systems need to work together to effectively transfer energy from the ground, through the lower extremities, to the core, and out the upper extremity. The pelvis and torso contribute as much as 50% to the kinetics of throwing.\textsuperscript{3,18} Any deficits along this kinetic chain can place added physical stress to other anatomical regions required to complete the task of throwing a baseball. Specifically in overhead throwing, an impaired ability to control the position of the trunk and legs can alter the position of the arm and potentially lead to injury of the shoulder and elbow.\textsuperscript{3,4,11,16,18-24} In order to properly screen, train, and rehabilitate a throwing athlete, an approach that examines balance, core stability, and lower extremity mobility and stability is necessary.\textsuperscript{16,19,22}

**METHODS**

The screen presented in this article will encompass testing of mobility and stability of the shoulder, trunk/core, and lower extremities. Athletes are taken through a series of tests and measure designed to assess critical components of a pitching delivery. These measures address tissue irritability, range of motion, coordination and strength. The rationale of these assessment techniques are described further in the discussion. While this screen examines much of the kinetic chain required to safely and effectively pitch, it does not cover all aspects of the chain such as a detailed examination of the thoracic spine or scapula. This is by design, as the purpose of a screen is to quickly identifies those at risk for injury so these deficits can be addressed, or the individual can be referred to a healthcare professional if needed.

**PROCEDURE**

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<td>The athlete lies supine with hips and knees flexed. The humeral head and coracoid process are palpated, but not stabilized, to determine the end-range of rotation. Goniometric Placement: Axis= olecranon process of the ulna. Stationary arm= perpendicular to the ground. Moving arm= along the ulnar shaft to the styloid process. The sum of passive glenohumeral joint external rotation and internal rotation at 90° of abduction in the plane of the scapula are measured and calculated. A side-to-side difference of more than 5° indicates greater risk for shoulder and elbow injury.</td>
</tr>
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<td>Description</td>
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<tr>
<td>----------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Passive Shoulder Flexion</td>
<td>The athlete lies supine with hips and knees flexed and the scapula lightly stabilized as the humerus is passively flexed to end-range. Goniometric placement: axis= acromion process, through the head of the humerus. Moving arm= longitudinal axis of the humerus. A side-to-side difference of more than 5° indicates greater risk for elbow injury.</td>
</tr>
<tr>
<td>Single Leg Stance Balance</td>
<td>Assessment is performed without shoes with eyes open looking toward direction of pitch. Hands together, hip flexion to 90°. The standard is set to 30 seconds with no Trendelenburg or trunk lean, and no major loss of balance. Test is performed bilaterally with quality and quantity being symmetrical. Poor single leg stance balance indicates poor core stability and neuromuscular control, indicating greater risk for shoulder injury.</td>
</tr>
<tr>
<td>Single Leg Stance - Anterior Lower Extremity Reach</td>
<td>Assessment is performed without shoes. The stance leg is the leg being tested, and the stance leg heel should remain flat at all times. The contralateral lower extremity reaches forward to slide a box as far as possible without touching the ground, kicking the box, or losing balance. Athlete returns to the starting position of the reaching foot on the ground next to the stance leg. Record the best of 5 reaches. A greater than 4 cm difference side-to-side indicates a greater risk for elbow injury.</td>
</tr>
<tr>
<td>Single Leg Stance - Upper Extremity Cross Over Reach</td>
<td>The athlete begins by standing on one leg, contralateral hip flexed to 90° with bilateral hand brought together over the flexed hip. The athlete reaches down and across in front of the stance leg with the contralateral upper extremity without touching the floor as the opposite leg moves backward for counterbalance. The athlete then returns to the starting position. There should be no major loss of balance, the trailing leg remains in the air at all times, the hand cannot reach down to touch the ground, and the athlete must successfully complete ten of twelve attempts bilaterally.</td>
</tr>
<tr>
<td>Single Leg Stance - Total Lower Extremity Rotation</td>
<td>A grid was created that has two lines 15° below the horizontal. The athlete’s lower extremity to be tested is placed in the center of the grid with the medial malleolus aligned with the horizontal line and the second toe in line with the vertical axis. The athlete flexes the contralateral hip to 90° with the tibia held perpendicular to the ground. Two markers are placed along the arc of motion the athlete’s raised tibia will follow in the transverse plane. One marker is placed on the horizontal line in the direction that the stance leg would move into relative external rotation and the other on the line 15° below the horizontal in the direction that the stance leg would move into relative internal rotation. The athlete will move the pelvis and torso into relative internal rotation of the stance leg so that contralateral, vertical lower leg contacts the maker at 15° below the horizontal, and then moves the pelvis and torso into relative external rotation of the stance leg to contact the other marker on the horizontal line. This is a pass/fail test, and the athlete must keep the airborne tibia vertical, contact both markers, and do so without a loss of balance three times bilaterally.</td>
</tr>
</tbody>
</table>
DISCUSSION

Shoulder Screening

The concept of Glenohumeral Internal Rotation Deficit (GIRD) has been well documented and is defined as a loss of internal rotation range of motion of the throwing arm compared to the non-throwing arm, anywhere from 12-20°. Historically, GIRD was thought to be a primary contributing factor to both shoulder and elbow injuries in overhead throwing athletes due to the concomitant hyperexternal rotation associated with the loss of internal rotation. GIRD has been attributed to tightness in the posterior glenohumeral joint capsule, myofascial restrictions, laxity of anterior glenohumeral joint capsule, and osseous changes that result in humeral retroversion. Humeral retroversion is due to the torque placed on the humerus with throwing during skeletal maturity resulting in apparent increases in external rotation with loss of internal rotation without true changes at the glenohumeral joint. Due to recent scientific evidence demonstrating that throwing athletes with GIRD do not exhibit capsular limitations, the latter theory has gained more popularity. Humeral retroversion and GIRD is normal and advantageous for the overhead pitcher, and may not be an adequate predictor of injury.

However, a significantly strong inverse relationship exists between humeral retroversion of the throwing arm and severe injuries to the shoulder (r=-0.90) and elbow (r=-0.85), indicating that greater humeral retroversion correlates with less severe arm injury. Pitchers with GIRD are just as likely to develop an elbow injury as those without GRID (odds ratio=1.0). Similar results regarding shoulder injuries were found when comparing those with and without GIRD (odds ratio=1.9), but these results were not statistically significant. Polster, et al. demonstrated a 30% reduction in injury risk for every 10° of humeral retroversion of the dominant arm compared to the non-dominant arm. These results suggest that GIRD due to osseous torsion may be advantageous for pitchers as humeral retroversion will allow the thrower to move through a longer throwing arc and achieve greater throwing velocity without additional physical stress to the glenohumeral joint and its supporting structures.

Total Rotational Motion (TRM), defined as the sum of passive glenohumeral external rotation and internal rotation at 90° of abduction in the plane of the scapula, is considered deficient if there is a side-to-side difference of more than 5°. The odds ratio for the development of a shoulder or elbow injury in a pitcher with a TRM deficit was 2.5 and 2.6 respectively, and both were found to be statistically significant. Interestingly, 78% of those pitchers that developed a shoulder injury had a throwing arm TRM greater than 176° suggesting that there is a limit to how much motion should be achieved. A flexion deficit is defined as a passive glenohumeral flexion range of motion side-to-side difference of more than 5°, and those pitchers with a flexion deficit were found to be significantly more likely to develop an elbow injury (odds ratio=2.8) when compared to those without a flexion deficit. These results are echoed in another study conducted by Garrison, et al.

The above evidence suggests that GIRD alone is not a valid predictor for the development of shoulder or elbow injuries in baseball pitchers, but measurements of TRM deficits and glenohumeral flexion deficits appear to be better predictors of injury. Based upon evidence, measurements of shoulder TRM and passive shoulder flexion would be more valuable and provide greater assessment of injury risk than measurements of GIRD and should be included in a pre-participation screen and made part of return to sport criteria.

Balance and Core Stability Screening

Assessment techniques such as single leg balance, front and side planks, and the Y-Balance test can be used to evaluate the static and dynamic lower extremity and core function. Prior studies have shown no significant difference between overhead athletes with a non-traumatic shoulder injury compared to those without an injury when it comes to measures of core function utilizing the front plank, side plank, double straight leg lower-
In the context of the throwing kinetic chain, without adequate lower extremity and core stability, energy transfer is compromised, which can place excessive physical stress on distal structures such as the shoulder and elbow.

The lower extremity and core function dynamically during overhead throwing and do so in multiple planes of movement. The Y-Balance is a reliable and valid test of dynamic lower extremity mobility and stability, core stability, and neuromuscular postural control in multiple directions, and has been shown to be a valid predictor of injury risk. High school baseball pitchers with a confirmed UCL tear demonstrated significantly decreased composite scores on the Y-Balance test on both lower extremities compared to pitchers without a UCL tear. The deficits in dynamic balance, lower extremity range of motion, core stability, and postural control associated with poor performance on the Y-Balance test can create dysfunctions throughout the kinetic chain and may successfully predict those overhead throwing athletes that are more likely to develop shoulder and elbow injuries.

In an effort to make this proposed screen efficient and allow for many athletes to be screened in a short amount of time, multi-directional testing of the Y-Balance test was reduced to a single plane of movement. Sagittal plane motion of the hip and knee can account for 90% of the variance seen in medial and lateral lower extremity reaches. In another study examining basketball players, only the anterior reach portion was predictive of injury, with those with a right/left reach difference of greater than or equal to 4 cm being three times more likely to be injured. This evidence justified the use of including only the anterior reach portion of the Y-Balance test to efficiently screen dynamic core lower extremity neuromuscular control. Recognizing that tri-planar function is necessary for efficient movement and performance, athletes would need to be further assessed in other planes when the screen identifies an individual with deficits.

**Hip and Lower Extremity Mobility and Stability Screening**

Several studies note the critical role of the pelvis and lower extremity sequencing during the overhead throwing delivery. Campbell, et al. used surface EMG on bilateral lower extremity musculature on healthy college baseball pitchers, demonstrating that during the early phases of throwing all lower extremity musculature demonstrate minimal to moderate activity, indicating that they are acting primarily as stabilizers. As the pitcher progresses through foot contact, cocking phase, and ball release, there is a gradual increase in nearly all trailing leg muscle activity to greater than 100% of Maximal Voluntary Isometric Contraction (MVIC) with the exception of the rectus femoris. On the stride leg at foot contract, the gluteus maximus, rectus femoris, and gastrocnemius demonstrated significantly high activity greater than 100% MVIC. All lower extremity muscle activity tested on the stride leg peaked from the cocking phase to follow-through, and all were well above 100% MVIC. It was concluded that the gradual increase in trial leg muscle activity from foot contact to ball release and the peak values of stride leg muscle activity through the follow-through phase suggest that the pitcher does not “push off the rubber” when throwing, but rather is more a “controlled fall.” The gluteus maximus of the trailing leg may contribute to pelvic rotation velocity, but the stride leg musculature is acting as a base that must eccentrically control the momentum of the forward moving pelvis, trunk, and upper extremity critical for generating ball velocity.

If the overhead throwing athlete does not possess the necessary mobility and stability to control the moving trunk over the striding lower extremity, the athlete may compensate by spending less time on the leg and/or changing the position of the trunk and arm. This in turn can place added stress on the shoulder and elbow with throwing and can lead to injury. One such compensation would be inadequate trunk flexion or adopting a more upright posture when throwing so as not to have to eccentrically control a forward flexing trunk over the striding leg. This specific compensation can lead to shoulder and elbow injuries in pitchers.

Other studies have described gluteal muscle activation and its relationships with pelvis and trunk kinematics during pitching, noting similar results as Campbell, et al. Stride leg gluteus maximus and medius activity were both greater than 150% of MVIC as the pitcher progressed from the foot contact to ball release phases of throwing, with the greatest activity at the late cocking phase of throwing. There was a statistically significant positive correlation between trailing leg gluteus maximus activity and increased pelvic rotation velocity at maximal glenohumeral external rotation (r=0.73) and at ball release (r=0.831). This suggests that the changes seen in pelvic rotation velocity are strongly related to gluteus maximus activity and account for a large portion of the variance seen in pelvic rotation during pitching.

The rate of pelvic rotation is significantly related to the rate of torso rotation (r=0.917) at the phase of maximal glenohumeral external rotation suggesting that hip and pelvic movement during throwing strongly impacts what happens at the torso, which can impact what happens at the throwing arm. Studies have found that if the sequence of pelvic and torso rotation is not timed appropriately, the pitcher will throw in an “open position” or a “closed position,” and place greater physical stress on both the shoulder and elbow that could potentially increase the risk for injury. Laudner, et al. demonstrated a positive correlation between total rotational hip motion of the lead leg measured in
prone with shoulder external rotation torque in National Collegiate Athletic Association (NCAA) Division I collegiate baseball pitchers \( (r=0.56) \). A significant relationship was also found with total rotational hip motion of the trailing leg and shoulder horizontal adduction during throwing \( (r=0.43) \). The authors concluded that limitations in hip mobility of the lead leg can place added torque on the shoulder, and that limitations in hip mobility of the trailing leg can cause pitchers to “throw across their bodies” and further stress the shoulder and limit performance. If hip rotation is not controlled during pitching, then the pitcher risks throwing in an “open position” which can prematurely initiate the cocking phase of throwing which has been shown to place greater torque on the shoulder and potentially lead to injury. Typically, transverse plane hip function is assessed with active and passive range of motion measurements in seated and in the prone positions. Isolated, open kinetic chain measurements of the hip would not adequately assess the transverse plane mobility and stability of the entire lower extremity kinetic chain. Thus, total lower extremity rotation mobility and stability needs assessed in a more functional, closed kinetic chain fashion in order to adequately screen for kinetic chain deficits and injury risk in throwers, which is depicted in this proposed screen.

Currently, there are no standards that exist for the degree of functional transverse plane lower extremity mobility and stability necessary to pitch. There is controversy in the literature as to whether rotation should be symmetrical bilaterally, and whether internal rotation should be equal to external rotation within a single lower extremity. Based on clinical experience, it was decided that a total lower extremity rotational arc of motion of 165° was needed to safely and effectively pitch with sound biomechanics. External rotation would account for 90°, and internal rotation would account for 75°. These measurements should be symmetrical bilaterally.

**Provocative Tests**

Two clearing tests were incorporated into this proposed injury screen, a shoulder impingement test and a valgus stress test to the elbow performed at 90° of elbow flexion. These two tests were added to determine the presence of pain and pathology within the shoulder and elbow, and will alert the screener to refer the athlete to a healthcare professional.

**CONCLUSION**

Baseball pitching requires a complex interaction of lower extremity mobility and stability, hip and pelvic mobility and stability, and core stability to effectively transfer energy from the ground, through the shoulder and elbow, and finally to the ball. If there is dysfunction anywhere along this kinetic chain, the potential for pain, performance reduction, and injury increases; especially at the shoulder and elbow. The proposed functional screen presented in this article can therefore be used to assess these major components essential to throwing, and can alert both coaches and athletes to potential injury risks.

**CLINICAL IMPLICATIONS AND LIMITATIONS**

Although the existing literature presented in this article is used to provide support for a functional kinetic chain injury screen for baseball pitchers, this evidence can be used to support rehabilitation principles for the inclusion of lower extremity and core training in the treatment of those with shoulder and elbow pathologies related to overhead throwing or similar activities. It can also be used to determine an athlete’s readiness to return to throwing following surgical procedures such as a UCL reconstruction. For instance, an athlete would have to successfully pass this proposed screen prior to the initiation of a return to throwing program.

**FURTHER RESEARCH**

There is little to no evidence that currently exists on the functional assessment of the lower extremity and core as it relates to overhead throwing. As such, there are no standards that exist regarding the degree of mobility and stability needed to throw while minimizing the risk for injury. The standards chosen for this screen were based on knowledge of sport and clinical experience in the treatment of baseball pitchers with shoulder and elbow pathologies. Further research is needed to ascertain evidence-based standards and the effectiveness of this screen at predicting injury.

**CONFLICTS OF INTEREST**

This article is originally written by the authors listed, and has not been published before. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the manuscript.

**CONSENT**

All participants depicted in the appendix are either one of the authors, or they have been de-identified.

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A Review of Mind Gym: Revisiting a Sports Management Classic

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Every sports fan remembers watching a game where one team that clearly dominated another in skill and power and then, magically, quickly, unexpectedly the other team won. Expert commentators and fans alike are left scratching their heads, “what happened?” Sports psychologists have the answer. Sports psychologists emphasize that being successful in sports is not only about the physical game on the field but also the inner game of psychology. In sports management classic, Mind Gym, Gary Mack¹ discusses mastering the inner game. Mack¹ uses his experience with top athletes and research on the psychological factors of success to teach the reader what it takes for athletes to master themselves and make the most of their physical skills so that they can achieve their potential on the field of their choice.

SUMMARY

Mack¹ begins his book in part by defining the inner game of sports so that the reader is well familiar with the importance of the mental game and how it affects success in sports. Mack¹ outlines an approach where he trains athletes mentally and checks their state of arousal so that they are equipped for the game but not over-aroused where their excitement converts to counterproductive nervousness. He talks about critical factors in the mental game such as emotional regulation and resilience, psychological concept of coping with stress and adversity. In part two, Mack¹ moves from describing the key components of the mental game and why they are important to discussing the necessity of accepting and enjoying success. This is an inspiring section wherein Mack¹ concentrates his energy on helping athletes realize that they are worthy of success and that their dreams are worth dreaming. In part three, Mack¹ builds on this point by continuing to emphasize the positive mindset that athletes need to embrace success. Finally in part four, Mack¹ addresses the idea of the “zone” (p. 161). The zone is a complicated concept because when athletes get into the zone they lose the sense of conscious thought that drives most of people’s performances in life. Mack¹ states that the zone is “no mind” (p. 170). Yet Mack¹ notes that it takes a great deal of ‘mind’ and focus on the mental game in order to get into the zone at critical times in the game. Mack¹ emphasizes that athletes practice the components of their mental game prior to the actual game so that when they get onto the field they are ready and can enter the zone of ‘no mind’ without compromising their mental acumen.

CRITICAL EVALUATION

Mack¹ begins the book with an enigmatic quote from Yogi Berra, “Ninety percent of the game is half mental” (p. 3). On one hand, this quote alludes to the importance of the inner game while the numbers appear to be incongruent. However, upon closer inspection Berra is actually saying that 10 percent of the game is luck (coincidence), whereas 90 percent is player controlled. Of the 90 percent, half of what the player invests in the game is physical but the...
other half is mental. Berra’s quote captures the essence of Mack’s message emphasizing the inner game without creating a formulaic approach and stating that athletes can learn to control the outcome of their games.

Mack’s emphasis on dreams and goals is another important component of this book. Having goals enables the athlete to struggle through adversity because he/she can concentrate on the goal and confront problems with a determined, persistent, tenacious attitude. These goals enable athletes to remain focused on change and to recognize when change has been achieved. Indeed, it is valuable to reflect on accomplishments. However, this requires the athlete to know where the journey begins and ends. Without this understanding, there can be no sense of achievement. As Mack builds on this point in part three, he asserts that “fear lives in the future” (p. 125). Athletes psych themselves out of a game, because they fear what may happen, not what is happening. For instance, when the opposing team scores at a critical time, athletes may fear that they will lose the game. This fear fuels an imagined loss instead of focusing on their confidence in their own abilities to win. This purports a powerful technique for change, growth, performance and the relationship between mental wellness (toughness) and optimum functioning.

CONCLUSION

Mack’s style of prose is to inform and inspire, but he works hard to avoid creating a rigid system of rules for athletes. The book’s thematic mental game is one that athletes should cultivate. It makes sense that if the controllable part of the game is half mental then athletes should spend time developing this part of their game. If practicing the physical game only accounts for half of athletes’ performance, ignoring the mental game may undermine their chances of success. Mack’s insight into managing adversity suggests that fear focuses on potential future problems and that doubt lives in a person’s lack of self-worth. Therefore, this book is highly recommended to anyone interested in sports psychology, athletes actively playing their favorite games, and anyone else interested in how the mental game affects their performance in their chosen careers. The practical nature of this book lends its utility to coaches and players, and may aid in designing interventions aimed at reducing inadequate thoughts, and feelings often experienced by athletes. This book would be applicable to any athlete struggling with performance, and goal-achievement.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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Defining Different Types of Interval Training: Do we need to use more specific terminology?

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KEYWORDS: Interval training; High intensity; Sprint intensity.

Interval training began gaining popularity in modern society throughout the mid 1900’s when track and field athletes started to incorporate them regularly into training programs. Soon after, Christensen, et al. published a study with a sample size of two concluding that “Research on intermittent work may open up a new field in work physiology” and in 1968 The Science of Swimming written by James Counsilman strongly advocated the use of sprints in training to optimize performance. This new found interest had peaked the curiosity of exercise physiologists and as a result a number of studies in the 1970’s utilized higher intensity intervals as training protocols. The consensus was that training intensity was a powerful tool to induce significant positive adaptations.

Traditionally high-intensity interval training has been generalized as repeated bouts of exercise 20 sec or longer in duration at an intensity above anaerobic threshold, but more specific definitions have been used. For example, high-intensity interval training (HIIT) can be considered an exercise at an intensity between our anaerobic threshold and maximal aerobic capacity (~80-100% of VO₂ max). However, sprint or supramaximal-intensity interval training (SIT) can be defined as an exercise >150% VO₂ max power. A comparison of HIIT and SIT reveals distinct differences between the exercises and using specific terminology for different types of interval training can increase clarity among researchers and the general public.

A review on Pubmed.gov of the 20 most recent articles to include HIIT in the title have utilized protocols of varying exercise intensities (~80-250% VO₂ max power) and duration (20-240 sec). Compounding the lack of clarity, the loose definition of HIIT can be commonly found in popular magazines that share training tips from published research. The conundrum is that two different types of training are being defined as the same.

HIIT programs that have resulted in positive adaptations utilized protocols that included 8-12 intervals that were 1-4 min in duration, while beneficial SIT protocols have typically included 4-10 intervals lasting 20-30 sec in duration. Acute responses to these protocols differ and each requires varying levels of aerobic and anaerobic contributions to energy production to complete the exercise. As a result, it is likely that unique levels of physiological stress result in some unique adaptations.

In general, similar chronic adaptations can be observed between HIIT and SIT programs lasting six weeks or greater. Both can improve aerobic, endurance and sprint capacity as well as markers of muscle metabolism and cardiovascular health in individuals of average fitness. However, training protocols that only last 2-3 weeks in duration have yielded different results. Following two weeks of training both HIIT and SIT appear to improve endurance capacity and markers of metabolism, but only HIIT has been observed to improve aerobic capacity. In addition, an investigation by Stepto, et al. observed trends that improvements in endurance and sprint capacity were greater with three weeks of HIIT (n=4) compared to SIT.
Improvements in aerobic and endurance capacity following two weeks of HIIT suggest that it may be better suited for improving cardiorespiratory fitness over a short period of time. This would fit the theory of “training specificity” since HIIT requires a significantly greater aerobic contribution compared to SIT.12,14 This same theory would suggest that SIT would be better at improving sprint ability compared to HIIT, but interestingly Stepto, et al. did not observe this trend. It is likely that their sample size was small and further research is warranted.13

In addition to different physiological responses following HIIT and SIT, the time commitment differs between the two programs. The average total exercise session (intervals and recovery between bouts) for HIIT last about 60 min and for SIT about 30 min. This can be a defining factor when deciding on the appropriate type of training. One could argue that SIT can be easier to complete because of the shorter training session, though the effort required to complete each interval may be greater.

An eloquent review of intense exercise training by Coyle concluded that “SIT performed all-out and repeatedly requires a high level of motivation, and it causes a feeling of severe fatigue lasting for at least 10-20 min. That is the ‘price’ for its effectiveness and remarkable time efficiency.”15 Through personal anecdotal experience completing both HIIT and SIT training protocols, I concluded that both are taxing and requires a great deal of perceived and actual effort, however the perceived exertion during HIIT was less than SIT. The trade-off is that the intervals are longer for HIIT (~1-4 min) compared to SIT (~20-30 sec).

When determining the optimal training program we must consider a number of factors including: the goals of the program; the time required to complete training sessions; the effort of completing the training; and the health and fitness of the participant in relation to their ability and willingness to complete the exercise. Because there are distinct differences between HIIT and SIT, one protocol may be more appropriate than the other.

For practitioners to avoid confusion between these two unique training programs, we should use specific terminology to distinguish each type of training. These two logical terms would be HIIT and SIT; HIIT include intervals above anaerobic threshold up to VO2 max and last 1-4 min in duration and SIT include intervals above 150% VO2 max power and last 20-30 sec in duration. By offering a clear distinction between these two unique training protocols, we can ensure that athletes receive the specific workout that best fits their needs.

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741.

Retrospective Designs in Sports Injury Surveillance Studies: All is not Lost

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Epidemiological research on sports injury and illness has significantly grown over the past two decades with increased recognition and support from sports governing bodies and international sports organizations. Collective evidence from different sports is suggestive that sports-related injuries can be prevented. Epidemiological studies are important to gain insights on the magnitude of the problem in terms of incidence rates, risk, severity and causes and subsequently to develop effective, sports-specific and sustainable injury prevention strategies. Therefore, sports injury surveillance methodologies should be appropriate to the sport as well as to the specific context especially in terms of age, gender, level of participation, tournament or season-based, cross-sectional or longitudinal and if a prevention program needs to be implemented.

Study designs that help address clinical research questions are broadly categorized into experimental and observational types. In sports injury research observational studies are most commonly either prospective or retrospective in nature. Retrospective studies collect historical data over a fixed period of time whereas prospective studies follow a cohort over a set future period of time. Prospective studies are generally considered to be of higher reliability as they can generate real-time knowledge of developments, closely monitor the exposure time, injury outcome and provide more accurate estimation of the risk and incidence. Retrospective injuries on the other hand mostly involve self-reported data based on athlete’s memory to recall the events. This can introduce memory recall bias with usually the major injuries being recalled leading to underestimation of the actual injury incidence and thus increasing the risk of the retrospective contamination. These issues may actually discourage many sports injury researchers to consider retrospective study designs.

While it is certainly preferable to plan a prospective approach to sports injury surveillance, they can be time-consuming, resource requiring and expensive to undertake owing to the length of data collection and the degree of monitoring involved. Retrospective studies on the other hand are time and resource efficient and may also encourage greater athlete participation compliance especially with team sports and elite athlete populations. Therefore, the value of retrospective designs cannot be undermined. A well-planned retrospective study design can have elements of reliability, validity and credibility to generate systematic high-quality data that may be valuable to provide insights into injury risk factors and mechanisms and develop injury prevention strategies. However, the issues with retrospective study designs should be pre-empted and methods appropriately conceived and implemented.

The key issue with retrospective study designs is memory recall bias. While it may not be possible to avoid it altogether, certain approaches in the methods can be used to minimize its extent. A recent study on competitive Dragon Boating, a traditional sport similar to rowing provides a good example of approaches to minimize the extent of recall bias in retrospective sports injury surveillance studies.

DEVELOP CONTEXT-SPECIFIC INJURY SURVEILLANCE QUESTIONNAIRE

Apparently most retrospective studies are based on self-reported data that is depen-
dent on the athlete’s ability to correctly recall the events. This may lead to recall bias and consequently invalid conclusions about injury epidemiology and the association between past and future injuries.\textsuperscript{9} An effective approach to provide a systematic and structured form to self-reported data would be to develop a context-specific injury surveillance questionnaire. This ensures consistency in reporting injuries. Many organizations have developed sports-specific injury surveillance systems\textsuperscript{10,11} that can serve as a credible basis to develop a customized questionnaire for retrospective injury data acquisition. Ascertaining the reliability and the validity of the questionnaire prior to its implementation can further add to the robustness of the method.

**DELIVERY OF THE QUESTIONNAIRES**

It is without doubt that physical distribution of questionnaires lead to 100% response rates and a higher likelihood of complete responses.\textsuperscript{9} Moreover, the physical presence of the research team members during distribution can serve to ensure completion and correctness of all data fields, clarify questions or doubts related to the type, nature and onset of injury, and exclude the non-sport related injuries. This increases the validity of the responses. However, physical distribution is a time and resource intensive exercise. Now-a-days, online options using the internet provide convenient and cost-free method of delivering the questionnaire to maximum number of recipients over a large geographical area. However, online survey methods in knowledge-based studies have reported low response rates.\textsuperscript{12} Online methods are yet to be used on a large scale especially in retrospective sports injury surveillance studies. A few studies have used online survey methods in community-based sports but no information has been provided on the response rates.\textsuperscript{13} Moreover, certain barriers related to time, technical issues, data entry and adjustments to the new system have been reported while implementing online surveillance tools.\textsuperscript{14}

**LIMIT THE LENGTH OF RECALL TIME**

While retrospective studies can gather data over any length of time in the past, limiting the length of time over which the athletes are asked to recall the events can reduce the recall bias.\textsuperscript{15} It is reasonable to speculate that a longer time frame has lesser likelihood of the accuracy of the recall. While the time frame of recall accuracy and validity is yet to be established, it is logical that shorter time frames have higher recall accuracy. However, evidence suggests a fair degree of success using a 12 month recall period.\textsuperscript{15,16} It therefore seems advisable to limit the recall time to 12 months in retrospective injury surveillance studies. This also implies that for season-based studies, the data should be collected as soon as possible on completion of the season.

**PROVIDE CLEAR INJURY DEFINITION**

The potential sources of error in injury surveillance data are unclear and inconsistent injury definitions, misinterpretations of injury types and misdiagnoses.\textsuperscript{17} These issues can be substantially minimized using the surveillance questionnaire. Providing clear and context-specific injury definition can facilitate better recall of the events through specific prompts.\textsuperscript{18} This strategy can also be used to provide clearly stated criteria for new/acute, recurrent, aggravation and overuse injuries\textsuperscript{4} thus enhancing the scope of the study. In addition to injury definition, additional information like providing a brief description of the onset and progress of the injury and if the injury led to missing training and competition likely to result in better recall and better elucidation of the details of the injury and thus enhance the validity of data interpretation. In addition, clear prompts regarding medical attention and time loss in the questionnaire can make it simpler for the athletes to provide information on the severity categorization of the injuries.

**ANATOMICAL LOCATION OF INJURY**

Many athletes may not be able to clearly distinguish and recall specific body parts. For example, the athlete may report upper limb injury but not able to specifically state whether it was the forearm, elbow or the shoulder. However, body part distribution of injuries is important information to explain the nature and mechanism of injury as some parts like the shoulder and lower back are more susceptible to overuse injuries. Providing an outline sketch of front and back of the human body and the list of different body parts in the questionnaire can stimulate better recall of the specific part injured. In this respect the presence of research team members during the occasion can also be helpful as the athlete can seek help to respond accurately.

**USE DIVERSE SOURCES OF INFORMATION**

It is quite natural that the athlete may not be able to recall all the injuries sustained in the past over a particular time frame. However, the accuracy of recall may be improved by asking the teammates, team captains, parents, trainers and coaches. In addition, many athletes tend to maintain regular training and event logs. Many a times the athletes also retain copies of medical documents in their diaries. These personal periodic logs and other relevant documents can serve as valuable references during injury documentation to improve the accuracy of the data and should be made use of in retrospective injury surveillance studies.

In summary, retrospective sports injury surveillance studies have the advantage of being time, cost and resource efficient and encourage greater participant compliance. However, the element of recall bias can significantly affect the validity of the data. It is therefore critical for sports injury researchers to pre-empt this possibility and adopt context-specific measures to maximize the accuracy, reliability and validity of the data.

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