1 **Throwing performance in water polo is related to in-water shoulder** 2 **proprioception**

3 Water polo players require a high level of upper-extremity strength, flexibility
4 and coordination to achieve a peak level of throwing performance. Increased
5 levels of shoulder proprioceptive acuity, strength and range of motion (ROM)
6 have been previously associated with higher sporting performance. A coach-
7 rating scale, used to quantify an athlete's kicking proficiency in soccer; was
8 adapted in the current study to measure each coach's subjective expert opinion
9 regarding athletes' throwing mechanics, velocity, and accuracy. To examine
10 this hypothesis shoulder proprioception acuity of 18 water polo players was
11 measured both in-water and on-land using an AMEDA apparatus and
12 correlated with coach-rated throwing performance and clinical measures of
13 shoulder strength and ROM. There was a moderate positive correlation
14 between the in-water and the on-land proprioception acuity ($r = 0.47$, $p <$
15 0.05). The in-water score showing a strong positive correlation with coach
16 rated throwing mechanics ($r = 0.68$, $p < 0.05$) and velocity ($r = 0.75$, $p = 0.02$),
17 suggesting that superior proprioception acuity contributed to fast,
18 mechanically-efficient throwing. These findings support the notion that in-
19 water proprioceptive acuity is an important determinant of the throwing
20 performance achieved by water polo athletes and its measurement may be a
21 valuable adjunct to current athlete screening.

22

23 Keywords: shoulder; water sport; proprioception; athletes, coaching expert
24 opinion

25

26 **Introduction**

27 The actions of overhead throwing, passing and swimming in water polo place
28 repeated loads on the shoulder complex (Miller, Evans, Adams, Waddington, &
29 Witchalls, 2017). To excel at the sport, athletes require sufficient joint range of
30 motion (ROM), muscle strength, endurance, and stability (Riemann & Lephart,
31 2002). Functional stability of the shoulder joint relies on the interaction of dynamic
32 (muscular) and static (capsulo-ligamentous, osseous, tendon) structures (Wilk, 1993),
33 mediated by the sensorimotor system (Riemann & Lephart, 2002). Proprioception is
34 an afferent input of this sensorimotor system that is of increasing interest within sport
35 and rehabilitative fields (Ager et al., 2017). For example, it has been shown that a
36 decreased proprioception sense can increase risk of injury (Safran, Borsa, Lephart,
37 Fu, & Warner, 2001), injury re-occurrence and contribute to poor recovery in
38 overhead athletes with shoulder pain (Fyhr, 2015).

39 The term proprioception has evolved to become an umbrella term which
40 includes the sub-modalities of joint position sense (JPS), sense of tension or
41 replication of force magnitudes (Dover & Powers, 2003), kinaesthesia (Riemann,
42 Myers, & Lephart, 2002), vibration detection (Clark et al., 2015) and changes in limb
43 velocity (Arzi, Krasovsky, Pritsch, & Liebermann, 2014). The assessment of
44 conscious proprioception is divided into three sub-components: JPS, the sensation of
45 movement (kinaesthesia), and sense of tension (Lephart, Pincivero, Giraido, & Fu,
46 1997). Kinaesthesia assesses the ability to not only detect movement but also the
47 direction, and is assessed by measuring threshold to detection of passive motion,
48 whilst JPS is assessed by measuring the accuracy of active or passive replication of
49 position. (Lephart, Pincivero, & Rozzi, 1998; Riemann et al., 2002).

50 Central processing may play a role in sporting performance (Han,
51 Waddington, Adams, Anson, & Liu, 2016). Indeed, proprioception is not just neural

52 input. A recent systematic review demonstrated the role of proprioception in
53 developing a neuromuscular response to a stimulus, involving sensory input, central
54 processing and motor response in a closed loop (Witchalls, Blanch, Waddington, &
55 Adams, 2012). Elite soccer players have been shown to dedicate less central
56 processing to proprioception but more attention to the technical aspects of the game
57 such as decision making and awareness of team positioning (Han, Anson,
58 Waddington, & Adams, 2014). Whether this is due to an athlete's intensive training,
59 and subsequent neuromuscular adaption, or to inherent genetic factors, is unknown
60 (Han, Waddington, Anson, & Adams, 2015).

61 The combination of proprioception, and accompanying neuromuscular
62 feedback mediated by the central nervous system (CNS), results in conscious
63 awareness of joint position and motion, and unconscious joint stabilisation through
64 spinal mediated reflexes (Lephart et al., 1998). Peripheral articular and
65 musculotendinous receptors provide afferent proprioceptive input to the CNS and
66 influence the reflex activity and joint stability during throwing activities (Myers &
67 Lephart, 2002). It has been hypothesised that the increased shoulder ROM observed
68 in throwing athletes as an adaptive response may, over time, induce trauma to the
69 shoulder capsule (Mota & Ribeiro, 2012). It is suggested that the increased ROM
70 may damage mechanoreceptors, consequently reducing afferent input and increasing
71 an athlete's throwing-related risk of injury (Mota & Ribeiro, 2012; Nocera, Rubley,
72 Holcomb, & Guadagnoli, 2006).

73 From a performance perspective, water polo athletes, like other throwing
74 athletes, have been found to have specific neuromuscular adaptations thought to be
75 important for skilled performance. For example, increased shoulder internal rotation
76 (IR) strength (Bloomfield, Blanksby, Ackland, & Allison, 1990), and increased ER

77 ROM in the dominant throwing shoulder (Witwer & Sauers, 2006) are proposed to
78 enhance performance by increasing ball velocity while allowing a longer acceleration
79 phase (Whiteley, Adams, Ginn, & Nicholson, 2010). Furthermore, proprioception
80 has also been associated with an athlete's level of attainment in sport (Han, Anson,
81 Waddington, Adams, & Liu, 2015; Han, Waddington, et al., 2015). This suggests
82 that a higher level of proprioception acuity contributes to enhanced motor control of
83 joints, and thus superior athletic performance (Waddington & Shepherd, 1996).
84 While proprioception acuity is unlikely to be the only determinant of throwing
85 success, the relationship between proprioception and successful performance in
86 water polo athletes warrants investigation (Whiteley, Adams, Nicholson, & Ginn,
87 2008).

88 Despite the importance of optimal biomechanical and neuromuscular
89 characteristics, such as an athlete's strength, ROM and throwing mechanics, the
90 overall evaluation of a player's ability, and subsequent team selection, is often based
91 largely on the expert opinion of the team coaching staff (Calder & Durbach, 2015).
92 There are a number of factors that influence this opinion, such as grading of
93 performance, anthropometry, tactical and psychological performance (Calder &
94 Durbach, 2015; Nash & Collins, 2006; Phillips, Davids, Renshaw, & Portus, 2010).
95 Additionally, it appears that a coach's rating of skilled performance may be
96 correlated with an athlete's proprioceptive ability (Cameron & Adams, 2003). For
97 example, in Australian Football, a positive correlation has been demonstrated
98 between coach-rated kicking performance and an athlete's level of proprioception
99 acuity measured using a purpose-built active movement extent discrimination
100 apparatus (AMEDA) to measure the swing leg JPS (Cameron & Adams, 2003).
101 Collectively, these findings support the notion that proprioceptive acuity is an

102 important determinant of the level of performance achieved by athletes and its
103 measurement may be a valuable adjunct to the current methodology of athletic
104 screening, due to its association with sporting ability.

105 To our knowledge, only one previous study has investigated shoulder
106 proprioception in water polo athletes, and this study focused on the relationship
107 between active joint repositioning error and shoulder strength in 20 male national
108 league athletes (Mota & Ribeiro, 2012). The main findings were correlations
109 between shoulder joint position error at 30° of external rotation (ER) and both
110 eccentric ER strength and concentric IR strength (Mota & Ribeiro, 2012). The
111 authors suggested that athletes with reduced proprioception may be more prone to
112 throwing-related injury due to a delayed neuromuscular protective reflex and
113 insufficient shoulder strength to decelerate the arm in the follow-through phase of
114 throwing (Mota & Ribeiro, 2012).

115 Given the potential importance of proprioception to both injury prevention
116 and successful performance (Fyhr, 2015), it is fundamental that proprioception is
117 measured accurately and reliably. In testing proprioception, it is important that the
118 tests maximise the similarity between the laboratory test and real-life function
119 (ecological validity) (Gibson, 1979). The AMEDA methodology aims to maximise
120 the ecological validity of proprioception testing through replicating activities similar
121 to the requirements of water polo (Han et al., 2016). The sport of water polo presents
122 athletes and coaches with a unique challenge of performing overhead throwing
123 activities within water rather than land as their base of support, requiring athletes to
124 simultaneously tread water whilst passing and shooting the ball. Recent evidence in
125 ankle proprioception suggests that dual task demands decrease an individual's
126 proprioception performance (Yasuda, Sato, Iimura, & Iwata, 2014). To date, no

127 previous study has measured shoulder proprioception of water polo athletes in their
128 aquatic playing environment.

129 The aims of the current study were to assess shoulder proprioception JPS,
130 both in-water and on-land, and to examine the relationship between proprioception,
131 shoulder strength, ROM, and coach-rated throwing performance. For the current
132 study, an AMDEDA apparatus (Whiteley et al., 2008) was adapted to enable
133 assessment of JPS during shoulder abduction and ER (throwing position), measured
134 whilst treading water. If JPS is important in throwing performance, then a
135 relationship between proprioception and throwing performance is expected.
136 Moreover, it is also anticipated that the coach's expert opinion/rating of a player's
137 skill will be positively correlated with the athlete's proprioceptive acuity level. This
138 research has implications for coaches, as proprioception training may refine neural
139 programs, allowing athletes to execute movement faster due to less conscious effort
140 being required (Han et al., 2016). Furthermore, proprioception testing may have a
141 role in talent identification and an athlete's likely skill acquisition within water polo.

142

143 **Methods**

144 *Participants*

145 Twelve male and six female players were recruited from a state level water polo
146 training squad (see supplementary material 1 for athlete demographics). Initial
147 contact was made via an email from the high-performance manager detailing the
148 proposed study. Potential participants were required to first fill out a questionnaire
149 containing demographic information, and to check for eligibility. To be eligible for
150 inclusion, athletes were required to have more than five years' playing experience
151 and be in water polo training a minimum of three days/week consistently over the
152 previous year. As a team, athletes were attending up to three strength sessions/week
153 and four or five pool sessions. An athlete's competition level was determined by
154 their highest playing level in the preceding 12 months (club, state, national level).
155 Athletes were excluded if they had shoulder pain or injury that prevented them from
156 participating in full unmodified team training, had experienced a severe injury, such
157 as shoulder subluxation/dislocation or surgery, in the preceding 12 months, or had
158 shoulder pain when adopting the required test position of shoulder abduction and ER.

159 Ethical approval and informed consent were obtained prior to commencement
160 of the study. The study was approved by the the University of Canberra Human
161 Research Ethics Committee (HREC 16-47) and all athletes were invited to provide
162 informed consent before being included in the study. Athletes were familiarised with
163 the AMEDA device and were tested during their team's training session 48-hours
164 after their last training session. All measurements were taken from the dominant
165 shoulder, defined as the player's preferred throwing/shooting arm.

166 ***Proprioception outcome measure***

167 Shoulder JPS was assessed with a purpose-built shoulder AMEDA shown in Figure
168 1. The AMEDA was configured for active proprioception testing (Naughton, Adams,
169 & Maher, 2002; Whiteley, Ginn, Nicholson, & Adams, 2009) and adapted so that it
170 could be used to assess athletes both in-water and on-land. The apparatus consisted
171 of a contact plate attached to the end of a hand-driven shaft used to set the stop point
172 for the hand when moving backwards with the elbow flexed to 90° and shoulder
173 externally rotated to 75°. The apparatus was mounted on either the pool edge (for
174 pool testing) or wooden boxes (for on-land testing) so that the height could be
175 individualised to ensure the dorsum of the hand contacted the middle of the contact
176 plate/disc (position one). The five stop settings (1-5) used were 2.0 cm apart, and
177 were located backwards of stop 1, thus progressively increasing the ER as the
178 distance withdrawn was increased (Figure 2). A height adjustable padded plate was
179 positioned at the lumbar-thoracic junction to ensure athletes remained centred with
180 respect to the device.

181 All male players were tested without a shirt, in their team allocated briefs,
182 and the females were tested in their team bathing suit. For the on-land testing,
183 athletes stood with their feet shoulder width apart, head facing straight ahead, eyes
184 fixed on a target on a wall 15m in front of them, so that they had no direct vision of
185 the hand or target plate. For the in-water testing, athletes were required to tread
186 water, eyes focussed on a target on the opposite side of the pool, 15m in front of
187 them. Proprioception was tested using both the in-water and the on-land AMEDA,
188 for the dominant throwing arm only. Total testing time was 40 minutes (20 minutes
189 per device) with 20 minutes rest between each apparatus. The order of the on-water
190 or on-land testing was randomised.

191 The AMEDA tests were conducted using active movements and all athletes
192 were given a standardised briefing and were familiarised with the test protocol.
193 Athletes were informed that there were five displacement distances, numbered 1
194 (smallest), 2, 3, 4, and 5 (largest), in increasing order of ER extent. Athletes were
195 then familiarised by performing three rounds on the device, moving from smallest to
196 largest distance, and making contact at each of the five stops (15 stops in total).
197 Athletes then undertook 50 trials without feedback, wherein all five stops
198 were presented 10 times in a random order. For each trial, the device was moved to
199 the stop position; the athlete then moved their arm from the starting position (hand
200 held at water level or hand held in front of the body in the same position as the pool)
201 and externally rotated their shoulder to touch the stop plate. Athletes then identified
202 the position as either position 1,2,3,4 or 5 by using their memory of the extent of
203 movement from the familiarisation series. The reported stop value was recorded, but
204 no feedback was given as to accuracy of the response. For consistency, the same
205 evaluator was used for each participant.

206 ***Shoulder strength and ROM***

207 Measurement of shoulder strength and ROM was conducted in the week prior to data
208 collection as part of the annual pre-season screening for the water polo program.

209 Neither the team physiotherapist nor the athletes were blinded to the ROM and
210 strength results. All athletes were measured by the same team physiotherapist, to
211 reduce protocol variation error. Before testing, athletes performed a 5-minute water
212 polo-specific warm up, and were familiarised with the testing procedures.

213 Passive shoulder IR and ER ROM were measured with the athlete lying
214 supine with their shoulder in 90° abduction, 90° elbow flexion and the forearm in
215 neutral (zero position). The shoulder was stabilised anteriorly by the physiotherapist
216 and no scapular movement was permitted. For IR, an inclinometer (TruMedical
217 Baseline® bubble 360°) was positioned centrally on the dorsal surface of the
218 forearm, 2cm proximal to the styloid process of the ulna. The testing position was
219 reproduced for ER on the ventral aspect (Kevern, Beecher, & Rao, 2014). Maximal
220 isometric shoulder IR and ER strength were measured using a hand-held
221 dynamometer (HHD; JTech Medical, Powertrack II Commander). Athletes were
222 required to sit on a plinth, with hips and knees at 90° and feet flat on the floor. The
223 arm was positioned so the shoulder was at 0° abduction, elbow flexed to 90° with the
224 forearm in a neutral position. For IR, the dynamometer was centred on the volar
225 aspect of the distal forearm, 2cm proximal to the radial styloid, and on the dorsal
226 aspect for testing ER. Athletes completed three maximal 5s isometric tests for both
227 IR and ER, which the physiotherapist met with equal and opposite force. A 5s rest
228 was given between the three tests and if a breaking contraction occurred, the reading
229 was omitted before executing the test again (Dollings, Sandford, O’Conaire, &

230 Lewis, 2012). Three measurements were performed and the average taken. All
231 measurements were recorded in kilograms force (kgf).

232

233 ***Coach rating of throwing performance***

234 Each coach, from the male and the female team, was surveyed to obtain their expert
235 opinion of each athlete's throwing skill. Coaches were asked to rate throwing
236 performance on a 1-10 scale. Ratings were obtained for each athlete regarding their
237 throwing accuracy, velocity, and mechanics. Athletes were also rated for overall
238 strength and flexibility. Coaches were instructed to record the overall impression of
239 each athlete's throwing, strength, and flexibility based on their observation of
240 training and competition. Please see the supplementary information for the full
241 coaches' survey.

242

243 **Data analysis**

244 For the in-water and on-land AMEDA testing, the perceived stop position was
245 tabulated against actual position in a stimulus-response matrix (Cameron & Adams,
246 2003). For both the in-water and on-land device, ability to discriminate between
247 adjacent angles (1–2, 2–3, 3–4 and 4–5) was determined by calculating the area
248 under the curve (AUC) of the receiver operating characteristics (ROC), with a curve
249 therefore generated for each paired comparison (Witchalls, Waddington, Adams, &
250 Blanch, 2013). The mean AUC score was then calculated from the four pair-wise
251 AUCs. This score gives the athletes' overall proprioceptive ability for shoulder
252 movements into ER (Witchalls, Newman, Waddington, Adams, & Blanch, 2012). An
253 AUC score of 0.50 is equivalent to chance performance and a score of 1.0 represents
254 perfect shoulder joint position discrimination.

255 The relationship between the AUC scores for the in-water and on-land
256 AMEDAs was investigated using Pearson product moment correlation coefficient
257 and r-values of 0.1, 0.3 and 0.5 were interpreted as small, medium and large
258 respectively (Cohen, 1992). A paired t-test was conducted on the AUC scores to
259 establish if there was any difference between the scores obtained in the two test
260 environments. A Bland-Altman plot was used to assess whether any differences were
261 consistent across the full range of scores.

262 To determine their relationship to shoulder proprioception in a throwing
263 position, the AMEDA AUC scores were also correlated with coach rated throwing
264 performance and athletes' measured shoulder IR strength, ER strength, and ROM.
265 All statistical analysis was performed using SPSS version 23.0 (SPSS Inc., Chicago,
266 IL, USA) with the level of significance set at $p < 0.05$.

267

268 **Results**

269 The mean proprioception score for in-water testing was 0.68 ± 0.06 and 0.71 ± 0.08
270 for on-land testing. No significant difference in mean scores between the two
271 environments ($p = 0.10$) was found, suggesting that the absence of a firm base of
272 support did not impair shoulder proprioception in these water-polo players. The
273 mean of the differences between scores for the two devices was 0.06 ± 0.08 (limits of
274 agreement, -0.03 to 0.15) and there was an even spread of difference scores around
275 the zero point on a Bland Altman plot (Figure 3).

276 A moderate positive correlation between the in-water and the on-land
277 AMEDA ($r = 0.47$, $p < 0.05$) was found. The in-water AMEDA score showed a
278 strong positive correlation with coach rated throwing mechanics ($r = 0.68$, $p < 0.05$)
279 and velocity ($r = 0.75$, $p = 0.02$).

280 Athletes' number of sport-specific training years was not correlated with
281 proprioception acuity score for either in-water ($r = -0.03$, $p = 0.91$) or on-land testing
282 ($r = -0.41$, $p = 0.09$). However an athlete's highest playing level in the last 12 months
283 was strongly correlated with in-water proprioception acuity ($r = 0.59$, $p = 0.01$).

284 Coach-rated strength was significantly correlated with the measured IR
285 strength obtained from manual testing ($r = 0.89$, $p < 0.01$). Coach-rated throwing
286 mechanics was significantly related to ER ROM ($r = 0.72$, $p = 0.04$) ER strength ($r =$
287 0.86 , $p = 0.04$) and coach rated throwing velocity ($r = 0.91$, $p < 0.01$). For these
288 players, coach-rated throwing accuracy was significantly positively correlated with
289 their IR strength ($r = 0.88$, $p = 0.02$) and coach rating of strength ($r = 0.76$, $p < 0.05$)
290 and was negatively correlated with coach-rated flexibility ($r = -0.76$, $p < 0.05$).
291 Players who the coach perceived to be more flexible were seen to have worse scores
292 for perceived accuracy. See Table 1 for all correlations.

293

294 <Insert Table 1>

295

296 **Discussion**

297 **Main findings:** The primary aim of the current study was to determine whether the
298 proprioception underpinning throwing was environment-specific, by correlating
299 scores obtained from an adapted in-water AMEDA device with the scores obtained
300 with an on-land device. A further aim was to better understand the relationship
301 between the variables: proprioception in a throwing posture, strength, and ROM, and
302 expert coaches' ratings of aspects of throwing performance. Water polo athletes
303 commonly exhibit sport-specific adaptive changes in their mobility, strength, and
304 proprioception (Miller et al., 2017), and many teams collect routine athlete screening
305 information in order to provide an indication of an athlete's overall and sport specific
306 capabilities. The current study confirmed the face validity of coach ratings as seen in
307 their relationship with proprioception scores. The in-water AMEDA proprioceptive
308 acuity scores demonstrated a strong positive correlation with coach-rated throwing
309 mechanics ($r = 0.68$, $p < 0.05$) and velocity ($r = 0.75$, $p = 0.02$) whereas the on-land
310 scores did not correlate with coach ratings. These findings suggest that good in-water
311 proprioception contributed to fast, mechanically-efficient throwing and gives further
312 weight to the importance of employing ecologically valid methodology when
313 assessing proprioception. Additionally, coach rated athletic strength was also
314 significantly correlated with athletes' clinical measures of IR strength ($r = 0.89$, $p <$
315 0.01), suggesting that manifestations of strength in defence and attack are visible to
316 coaches in this highly physical sport.

317 **Development of the in-water AMEDA:** Compared with passive tests and
318 supine tests, active-movement based measures of shoulder proprioception more
319 closely resemble normal function (Naughton et al., 2002), and thus have greater
320 ecological validity when assessing proprioception acuity in throwing athletes

321 (Whiteley et al., 2008). To assess shoulder proprioception actively, researchers have
322 previously measured JPS of overhead points using arm flexion (Naughton et al.,
323 2002) and ER (Whiteley et al., 2008) in standing participants. Overhead position JPS
324 with shoulder flexion demonstrated the importance of consistent preparation in
325 movement. What is unknown, however, is the relevance with a sporting population
326 (Naughton et al., 2002). The game of water polo requires athletes to perform
327 overhead throwing activities with water as the base of support. Thus, for the current
328 study, ecological validity (Han, Anson, Waddington, & Adams, 2013) was
329 maximised by modifying the AMEDA apparatus (Whiteley et al., 2008) to enable
330 testing in water. To reduce proprioceptive feedback and encourage athletes to
331 perform abduction/ER using their preferred movement pattern, arm movements were
332 completed without elbow support, as fixation may alter JPS (Tripp, 2006).

333 ***The role of the AMEDA in talent identification:*** One of the findings of the
334 current study was that there was a moderate positive correlation between in-water
335 and on-land proprioception test scores. Although athletes who scored well on the
336 proprioception test on-land also scored well on the in-water test, the water testing
337 procedure was seen as superior to the on-land testing due to its association with
338 coach-rated water polo throwing performance, and playing level achieved in the
339 previous 12-months, and thus it may better reflect skilled performance. These
340 findings are consistent with a previous study demonstrating that superior
341 proprioception acuity to be significantly associated with level of performance
342 achieved by athletes (Han, Anson, et al., 2015), and gives weight to the hypothesis
343 that proprioception testing may have a role in talent identification and an athlete's
344 likely skill acquisition. Future AMEDA studies in water polo are warranted across
345 multiple joints to investigate the relationship between proprioception acuity, training

346 years and level of sporting attainment, and could play a role in identifying talented
347 athletes.

348 ***Shoulder ROM adaptation and AMEDA testing:*** When comparing
349 performance of the dominant to the non-dominant shoulder, water polo athletes
350 consistently demonstrated adaptive change and increased dominant shoulder ER
351 ROM (Elliott, 1993; Witwer & Sauers, 2006). Explanations as to why overhead
352 athletes have a gain in dominant ER ROM have included osseous adaption (retro-
353 torsion) of the humerus from both genetic and overhead activity (Whiteley, Ginn, et
354 al., 2009) and accumulative micro-trauma to the soft tissue structures of the shoulder
355 from throwing activity (Witwer & Sauers, 2006). Gain in dominant shoulder ER
356 ROM has been associated with increased throwing performance level in baseball
357 players (Whiteley et al., 2010) and reduced injury risk (Wilk et al., 2015). Athletes'
358 throwing proficiency is improved due to increased ER ROM that is available in the
359 cocking action before strain is transferred to shoulder tissues (Whiteley, Adams,
360 Nicholson, & Ginn, 2009) and also gives a longer available acceleration phase
361 (Whiteley et al., 2010). In the current study, coach-rated throwing mechanics were
362 significantly correlated with clinical measures of athletes' ER ROM, and ER ROM
363 correlated with on-land proprioception but not in-water proprioceptive acuity. The
364 current findings are consistent with those from a previous AMEDA study on baseball
365 players, where it was found that non-dominant humeral retro-torsion and active
366 proprioception were positively and significantly correlated (Whiteley et al., 2008).
367 Further, with one outlier removed, the dominant shoulder retro-torsion scores
368 demonstrated a similar pattern and proprioception was moderately correlated with
369 retro-torsion (Whiteley et al., 2008).

370 ***Limitations of the AMEDA design:*** One limitation of the current study was
371 that the five predefined angles employed in the proprioception test cover a section of
372 the relevant range but are not adjusted for individual athletes' ER ROM. JPS has
373 been shown to be affected by the required range of shoulder elevation angle in
374 unconstrained tasks (Suprak, Osternig, van Donkelaar, & Karduna, 2006). In active
375 positioning tasks, afferent input may be different for athletes with larger ER (closer
376 to their mid-range) than athletes with less ER (closer toward their end ROM), due to
377 the muscle spindle playing a greater role in mid-range elevation and capsular-
378 ligamentous receptors being maximally stimulated toward the end of range (Lephart
379 et al., 1997; Safran et al., 2001; Whiteley et al., 2008). It has been proposed that
380 identification of players at risk of shoulder injury, due to sub-clinical injury, could be
381 achieved by targeting players with low proprioception/mean proprioception score,
382 despite sufficient ER ROM (Whiteley et al., 2008). Although study of prospective
383 shoulder injury was beyond the scope of the current study, given the association of
384 athletes' ROM to both performance and proprioception acuity, further research
385 investigating the relationship between ROM, proprioception, and injury in water polo
386 is warranted.

387 Since the use of the AMEDA is a new application of this test, it was not
388 possible to do an a priori power calculation. However, the values for variance within
389 this population, established by this study, can be used to calculate power for future
390 studies. The levels of significance seen in the current study indicate that the test is
391 able to discriminate performance differences in relatively small populations.

392 ***Shoulder strength and AMEDA testing:*** Findings from a previous study
393 suggested that water polo players with reduced shoulder strength have reduced
394 proprioception (Mota & Ribeiro, 2012). In contrast, the current study found no

395 association between measures of athletes' IR or ER strength and in-water or on-land
396 mean proprioception score. A possible reason for the difference in these findings
397 could be the different methodology employed, with Mota & Robeiro., (2012) using a
398 passive positioning and active reproduction protocol to assess angle reproduction
399 error (difference between actual and target at 30° ER) compared to the AUC score
400 obtained from JPS of five positions, as used in the current study. Whilst passive
401 positioning of the limb improves the reliability of testing, the clinical applicability to
402 real life function remains questionable (Ager et al., 2017). Moreover, athletes in the
403 current study were completing three strength sessions per week on top of the
404 plyometric training from pool throwing. Closed chain strength training has been
405 demonstrated to improve both function and proprioception in a short time frame
406 (Myers & Oyama, 2009), and 6 weeks of plyometric training improves
407 proprioception (Swanik et al., 2002). Potentially the team strength training program
408 may have confounded the results with regards to strength. Although, in the current
409 study, strength and proprioception were not correlated, the in-water proprioception
410 score and coach rated throwing performance were. A larger sample would provide a
411 more robust analysis of the association between proprioception and strength. Given
412 the known relationship between strength, performance, and proprioception, further
413 investigation regarding the current AMEDA protocol and targeted plyometric and
414 closed chain strengthening is recommended to determine if the in-water AMEDA is
415 sensitive to short term change. Potential exists for use of the AMEDA as pre-season
416 screening instrument as well as for obtaining return-to-sport baseline post injury.

417 **Conclusion**

418 The in-water AMEDA device score had a strong and positive correlation with coach
419 rated throwing speed and mechanics whereas results obtained from the on-land
420 AMEDA did not. The overall evaluation of a water polo player's ability, and
421 subsequent team selection, is often based largely on the expert opinion of the team
422 coaching staff. These findings support the notion that in-water proprioceptive acuity
423 is an important determinant of an athlete's throwing performance and its
424 measurement may be a valuable adjunct for coaches regarding current athlete
425 screening and future talent identification. Although beyond the scope of the current
426 study, reduced proprioception acuity has been proposed to increase the risk of injury
427 amongst water polo players. Further investigation regarding the in-water
428 proprioception device and humeral retro-torsion through indirect ultrasound
429 measurement with prospective injury follow up is warranted to explore this
430 hypothesis. This method would allow exploration of the association between physical
431 structure of the shoulder, shoulder proprioception and shoulder injury in water polo,
432 to evaluate the impact of achieving the shoulder angles that are used within water
433 polo throwing. Moreover, once the role of proprioception in shoulder injury is
434 established, plyometric training and proprioception development/retraining of water
435 polo players should be investigated.

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582 Table 1: Correlation of on-land and in-water proprioception, measured shoulder internal rotation (IR) and external rotation (ER) strength (ST)
583 and range of motion (ROM) with coach rated performance in water polo. Reported as r-value (p value).

		Coach rated performance					Athlete screening			
	AMEDA	Throwing			Characteristics		Strength		Range of motion	
	Land	Accuracy	Velocity	Mechanics	Strength	Flexibility	IR	ER	IR	ER
Water	0.47*(0.05)	0.30 (0.51)	0.75*(0.02)	0.68*(0.05)	0.30 (0.44)	-0.16 (0.69)	0.16 (0.56)	0.07 (0.79)	-0.35 (0.19)	0.33 (0.21)
Land		0.25 (0.60)	0.33 (0.39)	0.52 (0.15)	0.19 (0.63)	0.58 (0.10)	0.13 (0.63)	0.21 (0.43)	0.06 (0.82)	0.70*(<0.01))
Accuracy			0.36 (0.43)	0.41 (0.36)	0.76*(0.05)	-0.76*(0.05)	0.88*(0.02)	0.29 (0.57)	-0.16 (0.77)	0.07 (0.90)
Velocity				0.91*(<0.01)	0.47 (0.21)	-0.14 (0.72)	0.31 (0.41)	0.64 (0.09)	-0.10 (0.81)	0.55 (0.16)
Mechanics					0.52 (0.15)	-0.06 (0.87)	0.55 (0.15)	0.86*(<0.01)	-0.10 (0.81)	0.72* (0.04)
Strength						-0.32 (0.40)	0.89*(<0.01)	0.70 (0.06)	-0.10 (0.81)	-0.013 (0.98)
Flexibility							-0.28 (0.50)	0.27 (0.51)	0.02 (0.97)	0.55 (0.16)
IR ST								0.57* (0.02)	-0.43 (0.10)	0.01 (0.96)
ER ST									-0.32 (0.23)	0.29 (0.28)
IR ROM										-0.60 (0.82)

584

585 Figure 1
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589 Figure 2
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592 Figure 3

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596 Figure captions

597 Figure 1: The purpose built shoulder AMEDA device that can be adapted to both in-
598 water and on-land testing

599 Figure 2: The AMEDA apparatus mounted on either the pool edge to ensure the
600 dorsum of the hand contacted the middle of the contact plate. Position five of the five
601 (1-5) stop settings is demonstrated, as the athlete abducts and ER the shoulder.

602 Figure 3: Bland Altman plot of on-land and in-water proprioception of the dominant
603 shoulder, -- upper and lower level of agreement (LOA). AUC – area under the curve
604 (proprioception acuity).