

Bond University
Research Repository



A systematic review of the biomechanical research methods used in strongman studies

Hindle, Benjamin R; Lorimer, Anna; Winwood, Paul; Keogh, Justin W L

Published in:
Sports Biomechanics

DOI:
[10.1080/14763141.2019.1598480](https://doi.org/10.1080/14763141.2019.1598480)

Licence:
CC BY-NC-ND

[Link to output in Bond University research repository.](#)

Recommended citation(APA):

Hindle, B. R., Lorimer, A., Winwood, P., & Keogh, J. W. L. (2020). A systematic review of the biomechanical research methods used in strongman studies. *Sports Biomechanics*, 19(1), 90-119.
<https://doi.org/10.1080/14763141.2019.1598480>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

For more information, or if you believe that this document breaches copyright, please contact the Bond University research repository coordinator.

A Systematic Review of the Biomechanical Research Methods used in Strongman Studies

Benjamin R. Hindle^{a*}, Anna Lorimer^{a,b}, Paul Winwood^{b,c} and Justin W. L. Keogh^{a,b,d}

^aFaculty of Health Sciences and Medicine, Bond University, Gold Coast, Australia; ^bAUT University, Sports Performance Research Institute New Zealand (SPRINZ), AUT Millennium Institute, Auckland, New Zealand; ^cFaculty of Community Wellbeing and Development, Toi Ohomai Institute of Technology, Tauranga, New Zealand; ^dUniversity of the Sunshine Coast, Cluster for Health Improvement, Faculty of Science, Health, Education and Engineering, Sunshine Coast, Australia

Tel: +61 4 348 89190

Email: bhindle@bond.edu.au

ORCID ID: 0000-0001-9601-9985

Co-Author email addresses:

alorimer@bond.edu.au

paul.winwood@toiohohmai.ac.nz

jkeogh@bond.edu.au

1 **A Systematic Review of the Biomechanical Research Methods used in**

2 **Strongman Studies**

3 **Abstract**

4 As the sport of strongman is becoming increasingly popular, and such exercises are being
5 commonly used by strength and conditioning coaches for a wide range of athletic groups, a
6 greater understanding of the biomechanics of strongman exercises is warranted. To improve
7 the quality of research, this systematic review summarised the research methodology used in
8 biomechanical studies of strongman exercises and identified potential improvements to current
9 approaches. A search of five databases found ten articles adherent to the predefined inclusion
10 criteria. The studies assessed eight strongman exercises and included male participants of
11 relatively similar body mass but varying training backgrounds. Due to the complexity of
12 strongman exercises and the challenges in collecting advanced biomechanical data in the field,
13 most studies used simplified measurement/analysis methods (e.g. 2D motion capture). Future
14 strongman biomechanical studies should: assess under/un-researched strongman exercises;
15 include a greater number of experienced and female strongman athletes; utilise more advanced
16 (e.g. 3D motion capture and/or inertial sensor) technology so to provide a broader range and
17 greater quality of data. Such approaches will provide strength and conditioning coaches,
18 strongman coaches and athletes with a greater understanding of strongman exercises, thereby
19 further improving exercise prescription, athlete performance and minimising risk of injury.

20 *(abstract word count: 199)*

21 **Key words:** Kinematics, kinetics, motion analysis, weightlifting

22 **Introduction:**

23 Strongman is a competitive strength based sport consisting of exercises which are typically
24 heavier versions of common activities of daily living, traditional tests of strength or more
25 awkward/challenging variations of traditional weight training exercises such as the squat,
26 deadlift and clean and press (Harris et al., 2016). Common strongman exercises utilise
27 equipment such as; stones and loaded frames for lifting and carrying, logs and oversized
28 dumbbells for overhead pressing, tyres for flipping and vehicles and loaded sleds for pulling
29 (Keogh & Winwood, 2017).

30 With the increasing popularity of strongman as both a competitive sport and as a source of
31 alternative strength and conditioning training exercises for athletes of wide sporting
32 backgrounds, the quantity and quality of research on the sport of strongman is continuing to
33 increase. This research has examined the training and tapering practices of strongman athletes
34 (McManus, O'Driscoll, Coleman, & Wiles, 2016a; McManus, Wiles, Coleman, & O'Driscoll,
35 2016b; Waller, Piper, & Townsend, 2003; Winwood et al., 2018; Winwood, Keogh, & Harris,
36 2011; Zemke & Wright, 2011), how strength and conditioning coaches utilise strongman
37 implements in their athletes' programmes (Winwood, Cronin, Keogh, Dudson, & Gill, 2014b),
38 the physiological responses to strongman training (Berning, Adams, Climstein, & Stamford,
39 2007; Gaviglio, Osborne, Kelly, Kilduff, & Cook, 2015; Ghigiarelli, Sell, Raddock, & Taveras,
40 2013; Harris, et al., 2016; Winwood et al., 2015c; Woulfe, Harris, Keogh, & Wood, 2014) and
41 the injury epidemiology of strongman athletes (Winwood, Hume, Cronin, & Keogh, 2014c). It
42 should be acknowledged that some of this literature includes narrative reviews and/or opinion
43 pieces on how strongman exercises could be best integrated into strength and conditioning
44 programmes for non-strongman athletes.

45 Due to the emergent nature of the sport, wide range of exercises that may be performed in

46 competition or training, and the apparent complexity of strongman exercises, it is expected that
47 some level of between study variation may be encountered when attempting to biomechanically
48 analyse strongman exercises. Therefore, the primary objective of this systematic review was to
49 collect and assess information on the research methods used in existing studies which primarily
50 focus on the biomechanical analysis of a strongman exercise. By addressing this primary
51 objective, the current systematic review will summarise the; exercises, study designs, study
52 populations, and biomechanical analysis methods and measurements utilised in the existing
53 literature. The secondary objective of this systematic review is to identify the gaps in the
54 research methodology used in strongman biomechanical studies. By identifying these major
55 gaps, suggested improvements may be made to the current research methodology, better
56 equipping future researchers with the knowledge required to conduct more comprehensive
57 studies of greater quality on this sport. Such an approach will produce research which provides
58 greater insight into how strongman exercises may be used in wider strength and conditioning
59 or injury rehabilitation practice, as well as identify key biomechanical performance
60 determinants of these exercises for strongman athletes and coaches.

61

62 **Methods:**

63 ***Review protocol:***

64 A review protocol for this paper was developed using the 'Preferred Reporting Items for
65 Systematic Reviews and Meta-Analyses' (PRISMA) guidelines on reporting items for a
66 systematic review and the associated PRISMA checklist (Shamseer et al., 2015). This was used
67 in the planning and development of the systematic review to assure the quality of the review
68 process.

69

70 ***Search Strategy and Inclusion Criteria:***

71 An initial search was conducted using AusportMed, CINAHL, Embase, Medline (Ovid) and
72 SPORTDiscus up to and including 2 July 2018. Due to the lapse in time between the initial
73 search and submission for publication, a second search was conducted up to and including 25
74 October 2018. As the primary objective of this systematic review was to identify all strongman
75 articles in which biomechanical analyses were performed, a two-level keyword search using
76 Boolean operators was conducted. The first level of the search used terms associated with
77 strongman exercises, lifts and training methods, while the second level of the search used terms
78 associated with general biomechanical parameters. The full search strategy used for Medline
79 (Ovid) was: (strongman OR strong man.tw OR strong-man.tw OR junkyard OR junk-yard OR
80 junk yard OR log-lift* OR log lift* OR log press* OR log-press* OR yoke-walk OR yoke walk
81 OR yoke-carry OR yoke carry OR super yoke OR super-yoke OR frame lift* OR frame-lift*
82 OR frame carry OR frame-carry OR farmers walk OR farmers carry OR farmer's walk OR
83 farmer's carry OR suitcase carry OR duck walk OR frame carry OR hercules hold OR husafell
84 stone OR tyre flip* OR tyre-flip* OR tyre lift* OR tyre-lift* OR tire-flip* OR tire flip* OR
85 tire lift* OR tire-lift* OR car flip* OR car-flip* OR atlas ston* OR stone lift* OR conans wheel
86 OR conan's wheel OR fingal's fingers OR fingals fingers OR vehicle pull* OR vehicle-pull*
87 OR sled pull* OR sled-pull* OR sled tow* OR sled-tow* OR truck pull* OR truck-pull* OR

88 car pull* OR car-pull* OR chain drag* OR chain-drag* OR rope drag* OR rope-drag* OR
89 sand bag* OR sand-bag* OR sandbag* OR car lift* OR car-lift* OR vehicle lift* OR vehicle-
90 lift* OR truck lift* OR truck-lift* OR arm over arm pull OR arm-over-arm OR keg toss OR
91 keg-toss OR axle press* OR axle-press* OR dumbbell press* OR dumbbell-press*) AND
92 (biomechanic* OR bio-mechanic* OR kinetic* OR kinematic* OR anthropomet* OR emg OR
93 electromyograph* OR imu OR inertial measurement unit OR exp gait/ OR mechanic* OR force
94 OR velocit* OR force-velocity OR time OR exp motion/ OR exp torque/ OR power OR body
95 mass OR angular OR linear OR moment OR moment-angle OR moment angle OR moment-
96 arm OR moment arm OR momentum OR displac* OR equilibrium OR acceler* OR reac* OR
97 joint OR pressure OR inertia* OR work OR energy OR potential OR injur* OR impuls* OR
98 3D OR motion capture).

99 In accordance with the intended exhaustive nature of the search strategy, no limitations
100 were initially placed on language, year of publication, or literature source. To provide a
101 systematic review that captures the methodology used when assessing complex strongman type
102 exercises whilst being of value to the widest possible research community (and still adhering
103 the topic of strongman and biomechanics), no restrictions were placed on the age, gender and
104 lifting/athletic training experience of participants within a study. A set of guidelines outlining
105 the inclusion and exclusion criteria was established by the author (Table 1).

106

107 Please insert Table 1 about here

108

109 All articles returned from the five searched databases were imported into online
110 systematic review software Covidence (Veritas Health Innovation, Melbourne, Australia) and
111 distributed to two independent reviewers. The software automatically removed duplicate
112 articles before each reviewer began the title and abstract screening process. Reviewers voted

113 either 'yes', 'no' or 'maybe' to categorise each article's compliance with the pre-defined inclusion
114 criteria. Articles with vote combinations of 'yes'/'yes', 'yes/maybe' or 'maybe'/'maybe' were put
115 aside for full text screening while articles with vote combinations of 'no'/'no' were discarded
116 from further review. Articles not in the native language of the reviewers (English) were
117 returned by the respective database with sufficient translation for screening. Remaining articles
118 after title and abstract screening were then full text screened by reviewers with each reviewer
119 providing a reason for exclusion based on a hierarchical list of reasons. Where reviewers cast
120 conflicting votes (such as 'yes'/'no' or 'maybe'/'no') during title and abstract screening or full
121 text screening, or gave conflicting reasons for exclusion during full text screening, a consensus
122 meeting was held to reach an agreement between both parties. A final scan of the reference list
123 of all included articles was conducted to identify any relevant articles that were not initially
124 found in the database searches. Forward citation tracking using Google Scholar was then
125 employed to find any other articles that may have also been eligible to be included in the
126 review.

127

128 ***Quality Assessment:***

129 A risk of bias and quality assessment was undertaken by two independent reviewers. As no
130 standard checklist appeared entirely suitable for the eligible cross-sectional biomechanical
131 studies identified in this review, a checklist was developed by the authors based on systematic
132 reviews including literature of similar study designs (Ariëns, van Mechelen, Bongers, Bouter,
133 & van der Wal, 2000; Davids & Roman, 2014; DuRant, 1994; Gyorkos et al., 1994; Roman &
134 Frantz, 2013; van der Windt et al., 2000; Vandenbroucke et al., 2007; Wong, Cheung, & Hart,
135 2008). Where disagreements in the scoring was apparent between reviewers a consensus
136 meeting was held to establish agreement. An item was scored as one where the article provided
137 sufficient evidence in support of the criteria, and zero where the criteria was not met. A total

138 risk of bias score was calculated for each article and categorised using the methods of Davids,
139 et al. (2014), with articles scoring $\geq 67\%$ considered as having a low risk of bias, articles
140 scoring in the range of 34–66% considered as having a satisfactory risk of bias, and articles
141 scoring $\leq 33\%$ considered as having a high risk of bias. Only articles scoring a low or
142 satisfactory risk of bias were included in the review.

143

144 ***Data Analysis:***

145 To address the primary objectives of this systematic review, the data from the included articles
146 were categorised into four main sections: Exercises/Objectives, Study Population, Study
147 Design, and Biomechanical Analysis.

148

149 **Results:**

150 ***Literature Search:***

151 The five databases originally searched on 2 July yielded 786 titles of which nine were found to
152 be adherent to the inclusion criteria. After identifying another eligible study (Renals, Lake,
153 Keogh, & Austin, 2018) via a Google Scholar search, a second search of the five databases was
154 performed so to include Renals, et al. (2018) (in press) in the review. The updated search on
155 25 October resulted in the addition of one article to the systematic review after the original
156 search conducted on 2 July. A flowchart of the screening process undertaken on 25 October is
157 presented in Figure 1.

158

159 Please insert Figure 1 about here

160

161 ***Quality Assessment:***

162 Results from the risk of bias assessment are provided in Table 2. Generally, the articles

163 reviewed provided a testable hypothesis, used well validated data collection methods, utilised
164 appropriate statistical analysis methods, and presented results which were representative of the
165 tests performed. After conducting the risk of bias assessment on the ten eligible articles, eight
166 were assessed as having a low risk of bias ($\geq 67\%$), while two articles were assessed as having
167 a satisfactory risk of bias (34–66%).

168

169 Please insert Table 2 about here

170

171 *Exercises/Objectives:*

172 The ten eligible articles included in this systematic review have investigated eight different
173 strongman exercises. Although some of the strongman exercises were assessed in multiple
174 articles and some of the articles assessed multiple strongman exercises, the objectives, analysis
175 methods and comparative measures seen in many of the articles exhibited some degree of
176 between study variance.

177

178 *Exercises:*

179 The eight strongman exercises biomechanically analysed in the articles reviewed were the atlas
180 stone lift, farmers walk, heavy sled pull, keg walk, log lift, suitcase carry, tyre flip and yoke
181 walk (Figure 2).

182 *Atlas stone lift:* The atlas stone exercise requires the athlete to lift a large, spherical shaped
183 stone off the ground and on to a chest height or higher ledge. In competition the exercise is
184 usually performed as a series of stones of incremental mass which are lifted onto a series of
185 different height ledges, with some competitions also involving the maximum number of
186 repetitions within a minute performed with a stone of constant mass over a bar of constant
187 height (McManus, et al., 2016b).

188 *Farmers walk:* The farmers walk strongman exercise requires the athlete to pick up and move
189 heavy objects carried in each hand. In competition the exercise is most commonly performed
190 over a set distance of between 20 and 50 m, with the athlete striving to complete the distance
191 in the shortest possible time (Woulfe, et al., 2014).

192 *Heavy sled/vehicle pull:* The heavy sled/vehicle pull strongman exercise sees the athlete
193 attached to a vehicle (or weight loaded sled) via a chest harness. The heavy sled pull variation
194 is not often seen in competition, rather more commonly used as a training tool to simulate the
195 competition vehicle pull. In both the heavy sled and vehicle pull, the athlete is most commonly
196 required to pull the load a defined distance (often 20–25 m) in the shortest possible time
197 (McManus, et al., 2016b; Woulfe, et al., 2014).

198 *Keg walk:* The keg walk requires the athlete to carry a loaded keg on one of their shoulders. In
199 this event, athletes are typically required to either transport a maximum number of kegs from
200 one location to another in a defined period of time, or transport a defined number of kegs in
201 the shortest possible time (Havelka, 2004).

202 *Log lift:* The log lift strongman exercise requires the athlete to lift a metal or wooden log from
203 the ground and then push/press the implement above their head. In competition the exercise is
204 either performed as a maximal load for a single repetition, or a submaximal load for a maximum
205 number of repetitions in a defined period of time (often 60 seconds) (Havelka, 2004; McManus,
206 et al., 2016b).

207 *Suitcase carry:* The suitcase carry requires the athlete to carry a loaded weight in one hand. In
208 competition the exercise is typically performed for a defined distance in the shortest possible
209 time (Havelka, 2004).

210 *Tyre flip:* The tyre flip strongman exercise requires the athlete to repeatedly flip a tractor tyre
211 end over end. In competition this is typically performed over a defined distance, or for a defined

212 number of repetitions in the shortest possible time (Keogh, Payne, Anderson, & Atkins, 2010b;
213 McManus, et al., 2016b).

214 *Yoke walk*: The yoke walk requires the athlete to carry a loaded frame balanced across their
215 shoulders. In competition the exercise is either performed as a maximum distance in a defined
216 period of time, or a defined distance in the shortest possible time (Havelka, 2004).

217

218 Please insert Figure 2 about here

219

220 *Objectives*:

221 The earliest article on the biomechanics of strongman exercises was published by McGill,
222 McDermott, and Fenwick (2009) and aimed to use biomechanical parameters to estimate back
223 load, low-back stiffness and hip abduction torque when performing the atlas stone lift, farmers
224 walk, keg walk, log lift, suitcase carry, tyre flip and yoke walk exercises. Keogh, et al. (2010b)
225 used temporal measurements to determine possible factors which may affect athletic
226 performance of the tyre flip exercise, while similar studies by Keogh and colleagues (Keogh et
227 al., 2014; Keogh, Newlands, Blewett, Payne, & Chun-Er, 2010a) used both temporal and
228 kinematic measures to determine performance characteristics of the farmers walk and heavy
229 sled pull exercises, respectively. Winwood, Keogh, and Harris (2012) sought to quantify the
230 potential relationship between strength performance in weight training exercises and athlete
231 anthropometrics, and strongman competition performance of various strongman exercises
232 including the farmers walk, log lift, tyre flip and truck pull. A series of comparative studies
233 published by Winwood and colleagues compared biomechanical measures of a variety of
234 strongman exercises with those of technically similar traditional resistance training exercises
235 (Winwood, Cronin, Brown, & Keogh, 2014a, 2015a, 2015b). Most recently, Stastny et al.
236 (2015) conducted a study to determine if muscle strength ratios could be used to predict muscle
237 activation patterns during the farmers walk exercise, and Renals, et al. (2018) compared the

238 effect of log diameter on force-time characteristics of the push press phase of the log lift.

239

240 ***Study Population:***

241 The articles reviewed clearly detailed the number, age and body mass of participants included
242 in the study (Table 3). Although these variables exhibited some degree of variance between
243 studies, all studies consisted of male participants, with no studies including female participants.
244 Participants included in the articles reviewed typically had at least moderate levels of general
245 resistance training, one repetition maximum (1RM) testing or strongman type functional
246 training experience with many also having a combination of powerlifting and/or strongman
247 competition experience.

248

249 Please insert Table 3 about here

250

251 ***Study Design:***

252 All articles reviewed were of a cross-sectional observational study design. The general
253 structure of each study design consisted of a warm up protocol and a test protocol. The warm
254 up protocol outlined in each study was of a general nature and inferred basic structural
255 consistency for all participants. The test protocol of most studies detailed the number of sets
256 and repetitions of a given exercise, the allocated rest period between sets/bouts of exercise and
257 the prescribed implement load (Table 4).

258 The number of repetitions, sets and the way in which a set was defined varied between
259 many of the articles reviewed. The variation in the definition of a set was generally seen in the
260 studies whereby walking type strongman exercises were assessed. As strongman walking
261 exercises such as the farmers walk, keg walk, heavy sled/vehicle pull, suitcase carry and yoke
262 walk are typically performed once over a specific distance, the distance in which participants
263 were required to perform these exercises during a trial varied between studies. Less variation

264 was however seen in the definition of a set in the studies in which participants were required
265 to perform repetitions of a static lift such as the log lift, stone lift and tyre flip.

266 Methods used to determine the loading of implements included the use of a constant
267 absolute implement load for all participants (Keogh, et al., 2014; Keogh, et al., 2010a; Keogh,
268 et al., 2010b; McGill, et al., 2009; Winwood, et al., 2012), a set percentage of a participant's
269 1RM (Renals, et al., 2018; Winwood, et al., 2014a, 2015a, 2015b), or an incremental load based
270 on the participant's six repetition maximum (6RM) (Stastny, et al., 2015). These loads were
271 generally established in a familiarisation session held in the week/s prior to the testing session.

272

273 Please insert Table 4 about here

274

275 ***Biomechanical Analysis:***

276 The reviewed articles analysed a variety of biomechanical parameters (Table 5) using a number
277 of different measurement techniques and equipment. The biomechanical parameters seen in the
278 articles reviewed have been categorised and presented for discussion using a deterministic
279 model approach. The deterministic model is based on how the different categories of
280 biomechanical measures may affect the ultimate performance outcome of the exercise (Figure
281 3).

282

283 Please insert Figure 3 about here

284

285 *Temporal Measures:*

286 Temporal data of the tyre flip (Keogh, et al., 2010b), farmers walk (Keogh, et al., 2014;
287 Winwood, et al., 2014a) and heavy sled pull (Keogh, et al., 2010a; Winwood, et al., 2015a)
288 were collected using a series of cameras to capture two-dimensional (2D) data in the sagittal
289 plane. Computer software was used to post process the video data and record the time taken

290 for the athlete to complete each defined phase of the lift or section/phase of the walk/pull.
291 Temporal data for the fastest and slowest farmers walk, heavy sled pull and tyre flip trials were
292 compared within and between participants in the studies by Keogh and colleagues (Keogh, et
293 al., 2014; Keogh, et al., 2010a; Keogh, et al., 2010b), while Winwood, et al. (2014a) made
294 group-average temporal data comparisons of the farmers walk to that of an unloaded walk, and
295 Winwood, et al. (2015a) compared measures between phases of the heavy sled pull. Propulsion
296 phase duration and total lift duration were measured for the log lift push press in Renals, et al.
297 (2018), with such measures calculated from force plate data and compared between a barbell
298 and various diameter logs.

299

300 *Athlete/Implement Linear Kinematics:*

301 Athlete linear kinematics were collected for the farmers walk (Keogh, et al., 2014; Winwood,
302 et al., 2014a) and heavy sled pull (Keogh, et al., 2010a; Winwood, et al., 2015a) by method of
303 marker based tracking using 2D sagittal plane video camera data and post processing computer
304 software. This equipment and methodology was also commonly used to collect joint/segment
305 angular kinematic data as described subsequently. The analysis performed on the
306 athlete/implement kinematic measures for the farmers walk and heavy sled pull were as per the
307 temporal measures presented previously for each respective study (Keogh, et al., 2014; Keogh,
308 et al., 2010a; Winwood, et al., 2014a, 2015a).

309 Renals, et al. (2018) measured athlete linear kinematics during the log lift push press in
310 the form of vertical velocity and displacement of the athlete's centre of mass. These
311 measurements were calculated by subtracting the body mass of the athlete and the load lifted
312 from the vertical force data leaving the measurement of acceleration, which were then
313 integrated to give vertical velocity and integrated once again to give displacement. These
314 measurements were presented as mean values during the braking and propulsive phases of the

315 lift. Bar/log path trajectory and velocity data in Winwood, et al. (2015b) were collected by
316 sagittal and frontal plane video recording and processed using computer software. Implement
317 trajectory was plotted as vertical and horizontal displacement as both a function of time and
318 relative to the initial starting point, while velocity data were presented as peak and mean
319 vertical velocity values throughout each phase of the lift.

320

321 *Joint/Segment Angular Kinematics:*

322 Joint/segment angular kinematic data in the studies by Keogh and colleagues (Keogh, et al.,
323 2014; Keogh, et al., 2010a), and Winwood and colleagues (Winwood, et al., 2014a, 2015a,
324 2015b) were collected using 2D video camera data techniques described in the
325 athlete/implement linear kinematics section. The number of markers used to locate and track
326 anatomical locations of the athlete's body ranged from six to 12 with anatomical positioning of
327 these markers varying depending on the exercise being analysed and the biomechanical
328 parameter being assessed. These measures were presented as a range of motion throughout an
329 exercise or an angle at defined instances throughout an exercise.

330 Lumbar spine angular data were collected in McGill, et al. (2009) using a 3Space
331 IsoTRAK electromagnetic tracking system (Polhemus, Inc., Colchester, Vt, USA). The system
332 consisted of a transmitter secured to the pelvis over the sacrum of the participant, and a receiver
333 secured over the T12 spinous process of the participant, allowing for relative position of the
334 lumbar spine to be approximated. In addition, a two video camera system that enabled vision
335 of the frontal and sagittal plane was used to record and synchronise electromyography (EMG)
336 data and spinal posture data obtained from the electromagnetic tracking system. These
337 measures were presented as peak flexion-extension, medial/lateral bend, and twist of the
338 lumbar spine.

339

340 *Athlete Kinetics:*

341 Kinetic measurements within the body of the athlete (in the form of muscle and joint loads)
342 and forces acting externally on the body (in the form of ground reaction forces) were reported
343 in five studies (McGill, et al., 2009; Renals, et al., 2018; Winwood, et al., 2014a, 2015a, 2015b).
344 Muscle and joint force, and torso stiffness estimations in McGill, et al. (2009) were derived by
345 first inputting the collected EMG data and spine angular kinematic data into a distribution
346 moment (DM) model (Ma & Zahalak, 1991). Resultant muscle force and stiffness
347 approximations from the DM model along with spine angular kinematic data were then input
348 into a lumbar spine model based on anatomical approximations to optimise individual muscle
349 force and stiffness. The 18 degree of freedom model utilised an EMG based function to balance
350 the external moment equation of a rigid link model (described subsequently) with the moments
351 produced by the initial muscle and joint force estimations. This method ensured preservation
352 of muscle recruitment patterns seen in the EMG data by adjusting individual muscle force and
353 stiffness coefficients.

354 Estimations of joint reaction moments about the lumbar spine (L4/L5) were derived in
355 McGill, et al. (2009) through the input of digitised spine postural data and anthropometric
356 approximations into a rigid link body model using similar techniques to McGill and Norman
357 (1985). These moments were estimated for flexion/extension, medial/lateral bend and twist.
358 Joint reaction moments of the hip were estimated by first recording a maximum voluntary
359 isometric hip abduction effort for each participant. Kinematic joint angle data in the frontal
360 plane from each of the walking exercises were digitised and input into the rigid link body model
361 to estimate the hip abduction moment experienced throughout each exercise. These results were
362 then normalised to the maximum isometric voluntary hip abduction produced by each
363 participant and expressed as a percentage of the participant's maximum isometric voluntary hip
364 abduction.

365 Three studies used a Bertec force plate (Model AM6501, Bertec Corp., Columbus, OH,
366 USA) to collect ground reaction force data in the vertical, medial/lateral and anterior/posterior
367 directions (Winwood, et al., 2014a, 2015a, 2015b), while one study used a Kistler force plate
368 (Model 9851B, Kistler Instruments Ltd., Hook, United Kingdom) to collect vertical ground
369 reaction force data (Renals, et al., 2018). The data were post-processed using computer
370 software and normalised for time, with forces presented in their respective axial directions
371 depending on the exercise and study. Additionally, the log lift studies of Renals, et al. (2018)
372 and Winwood, et al. (2015b) used the ground reaction force data and implement velocity data
373 to estimate power and impulse throughout various phases of the lift.

374

375 *Muscular Activity:*

376 Electromyography measurements were collected in McGill, et al. (2009) using sixteen
377 electrode pairs placed bilaterally on various abdominal, back and gluteal muscles. Standard
378 EMG practices were generally reported throughout the preparation, collection and processing
379 of the EMG data, with EMG signals full wave rectified and low-pass filtered using a second-
380 order Butterworth filter. These EMG signals were then normalised for each participant to a
381 maximal voluntary contraction (MVC) of each muscle, providing insight into key muscular
382 contributors during various strongman exercises. As detailed previously, these measurements
383 were also used to calculate internal force and stiffness experienced by individual muscle
384 fascicles of the lumbar spine during each exercise.

385 Stastny, et al. (2015) collected EMG data during the farmers walk exercise. A Noraxon
386 Myosystem 1400A (Noraxon, Scottsdale, AZ, USA) EMG system was used to collect raw
387 EMG data from four electrode pairs placed bilaterally on selected hamstring, quadricep and
388 gluteal muscles. Standard EMG practices were generally reported throughout the preparation,
389 collection and processing of the EMG data with data band-pass filtered and smoothed using a

390 root mean square approach. Participants were required to perform MVC at 75° knee
391 flexion/extension and 15° hip abduction on an IsoMed 2000 Dynamometer (D & R Ferstl
392 GmbH, Hemau, Germany) prior to farmers walk testing to establish muscular strength ratios
393 of the hamstring/quadricep, hip abductor/quadricep, and hip abductor/hamstring. Participant
394 EMG data taken during the farmers walk trials were then normalised to MVC testing data and
395 used to determine if a relationship could be established between lower limb muscle strength
396 ratios and muscle activation patterns during the farmers walk.

397

398 *Athlete Anthropometric Measures:*

399 Athlete anthropometric measures of stature (height), body composition and body segment
400 girths were taken in one of the articles reviewed (Winwood, et al., 2012). Stature measurements
401 were taken using a portable stadiometer (Seca 214, Hangzhou, China), body segment girths
402 were taken using a Lufkin tape measure (Cleveland, OH, USA) and body composition
403 measurements were taken using a bioelectrical impedance machine (InBody230, Biospace,
404 Seoul, Korea). All anthropometric data were collected by a qualified International Society for
405 the Advancement of Kinanthropometry anthropometrist, with the measurements used to
406 determine if a relationship existed between athlete anthropometry and that of maximal strength
407 in traditional weight training exercises, and strongman exercise performance.

408

409 Please insert Table 5 about here

410

411 **Discussion and Implications:**

412 The methodology used to collect data for the biomechanical analysis of a movement may have
413 significant implications on the quality of the data and its applications to improving athletic
414 performance and/or reducing injury risk. The methodology selected by researchers may be

415 influenced by the exercise being analysed, the objective of the study, study population, study
416 design and biomechanical measures desired, with each area discussed in order in the following
417 section. By exploring the methodologies used in biomechanical studies of traditional weight
418 training exercise, future biomechanical studies may produce a higher quality of data, which
419 should result in a more comprehensive understanding of this sport and therefore improve
420 strongman performance and wider strength and conditioning practice.

421

422 ***Exercises/Objectives:***

423 A large portion of the articles reviewed conducted biomechanical analysis on the farmers walk
424 and heavy sled pull exercises (Keogh, et al., 2014; Keogh, et al., 2010a; McGill, et al., 2009;
425 Stastny, et al., 2015; Winwood, et al., 2014a, 2015a; Winwood, et al., 2012). This is possibly
426 due to the common occurrence of these exercises in the strength and conditioning programmes
427 of non-strongman athletes (Winwood, et al., 2014a). Although biomechanically assessed in
428 two of the ten articles reviewed, the heavy sled pull exercise is not typically seen in strongman
429 competition, rather it is more commonly used as a training exercise for the vehicle/truck pull
430 seen in competition. The heavy sled pull and the vehicle/truck pull may differ in terms of their
431 performance determinants to some extent due to differences in the frictional behaviour of the
432 two loads. To put a heavy sled in motion, static and dynamic sliding friction must be overcome,
433 with typical coefficients of friction between a heavy sled and an athletic track found to range
434 from 0.3 (static) to 0.47 (dynamic) (Cross et al., 2017). When compared to the coefficient of
435 rolling resistance of a vehicle tyre (~0.004) (Hall & Moreland, 2001), it may be appreciated
436 that in order to overcome the initial inertia of an object of equal mass, a force 75 times greater
437 must be applied to a sled (to overcome static sliding friction) than to a wheel (to overcome the
438 friction apparent as rolling resistance). However, the mass and coefficient of friction are not
439 the only variables that must be considered when assessing the replicability of a heavy sled pull

440 to that of a vehicle pull. A phenomenon known as stick-slip must also be considered. This
441 phenomenon occurs as a result of an object in sliding contact generally having the inability to
442 momentarily continue to move once a propulsive force is no longer applied to the object as
443 would typically be seen with a wheel (Cross, et al., 2017). As a result of these behavioural
444 differences, the contribution of the current heavy sled pull studies toward improving
445 researcher's understanding of the key biomechanical determinants of the strongman
446 competition vehicle pull is still somewhat unclear.

447 Although the results from McGill, et al. (2009) made reference to some of the
448 biomechanical differences seen between athletes of varying competition standard, the results
449 were not statistically compared. The resultant back load, low-back stiffness and hip abduction
450 torque measurements reported by McGill, et al. (2009) were compared between exercises. In a
451 similar fashion, the biomechanical measurements taken in Renals, et al. (2018), and Winwood
452 and colleagues (Winwood, et al., 2014a, 2015a, 2015b) were compared between strongman
453 and traditional exercises, with no comparative analysis being undertaken between athletes of
454 varying performance levels. Stastny, et al. (2015) also did not measure or compare overall
455 athlete performance, but rather compared muscular activation patterns between athletes of
456 varying muscular strength ratios. The recommendations seen throughout these studies appear
457 to be more directed at strength and conditioning coaches for targeted performance
458 improvements in non-strongman athlete training programmes or for injury
459 rehabilitation/prevention for both strongman and non-strongman athletes.

460 Contrary to McGill, et al. (2009), Renals, et al. (2018), Stastny, et al. (2015), and
461 Winwood and colleagues (Winwood, et al., 2014a, 2015a, 2015b), Keogh and colleagues
462 (Keogh, et al., 2014; Keogh, et al., 2010a; Keogh, et al., 2010b) compared biomechanical
463 measures between athletes of varying performance standards. Across these three studies it was
464 found that a number of biomechanical differences exist between athletes of varying

465 performance levels which likely contribute to the overall performance of the athlete. The results
466 from Keogh and colleagues (Keogh, et al., 2014; Keogh, et al., 2010a; Keogh, et al., 2010b)
467 may be of particular value to strongman coaches and athletes wanting to improve competition
468 performance.

469 Future strongman studies should look to focus on popular strongman exercises with
470 little to no previous research conducted in the field. Such exercises may include the atlas stone
471 lift, single arm dumbbell press, yoke walk and variations of the vehicle pull which are more
472 representative of that seen in strongman competition. Additionally, future studies may consider
473 comparing biomechanical measures between higher and lower performing athletes as has been
474 performed in few studies (Keogh, et al., 2014; Keogh, et al., 2010a; Keogh, et al., 2010b).
475 Identifying key biomechanical performance determinants of strongman exercises would be
476 expected to improve coaching and the overall performance of strongman athletes at all levels
477 of competition. Information on how to better perform strongman exercises may also be used
478 by special forces, police departments and emergency services personnel who are faced with a
479 life and death situation whereby they are required to move heavy, awkwardly shaped objects
480 and/or carry or drag civilians to safety. Such tasks may be seen to closely replicate some of the
481 exercises undertaken by strongman athletes (Keogh, et al., 2014).

482

483 ***Study Population:***

484 The articles reviewed generally consisted of a small sample size (six or fewer participants).
485 Two of the articles reviewed included a larger number of non-strongman athletes ($n = 16$; $n =$
486 23) (Stastny, et al., 2015; Winwood, et al., 2012) with backgrounds in other forms of resistance
487 training. Although results from these non-strongman populations may be of relevance to
488 strength and conditioning coaches who are contemplating including strongman exercises into
489 an athlete's training programme, the results from these studies may not be representative of, or

490 generalisable to the competitive strongman athlete population. In addition, the inclusion of non-
491 strongman athletes in some of the studies reviewed likely had a small carry-over effect on
492 subsequent methodology used in the study, such as the warm-up methods and the loads used
493 when performing a given exercise. These considerations will be discussed further in subsequent
494 sections. The small number of competitive strongman athletes included in the articles reviewed
495 may be due to the sport of strongman still being young and the limited number of athletes
496 competing in the sport of strongman in any given geographical location. With the increasing
497 popularity of the sport of strongman it may be expected that future studies will include a greater
498 sample size of national and international level competitive strongman athletes, including
499 female and lighter male participants than have been included in previous studies. Studies of
500 typical strongman athletes would provide results which are of greater relevance to strongman
501 coaches and athletes.

502

503 ***Study Design:***

504 All articles included in the review were of cross-sectional design. This type of study design is
505 commonly utilised in biomechanical research and provides a snapshot of athlete performance
506 and biomechanical parameters at a single point in time. These performance outcomes may be
507 affected by how an athlete is feeling on a particular day and may be influenced by factors such
508 as sleep, stress, nutrition, training load, injury or illness. No articles published to date have
509 assessed and/or compared biomechanical parameters of an athlete performing a strongman
510 exercise over an extended period of time. Future studies may consider assessing strongman
511 training performance and biomechanical parameters at regular intervals throughout the training
512 and competition season of an athlete. The results from such studies may be of particular interest
513 to strongman coaches when programming training blocks for athletes, determining associations
514 between strongman technique and performance, and also in assessing signs of adaptation, over-

515 training, fatigue and injury. Strength and conditioning coaches may also be interested in such
516 longitudinal studies as they would provide greater insight into the benefits and potential injury
517 risks of such exercise programmes.

518 The way in which implement loading was determined in the articles reviewed exhibited
519 some degree of between study variation. The majority of loads used were somewhat reflective
520 of the experience and/or competitive standard of the athletes tested, with studies that included
521 a greater number of non-strongman athletes typically seeing lighter loading. Many of the
522 articles reviewed lacked detail on the methods used to establish implement load. These details,
523 along with justifications for the use of the method should be reported to provide the reader with
524 a greater context to the study. Prescribing implement loading based on pre-test 1RM tests could
525 be a useful approach in some studies, as it would provide a way to normalise the data collected
526 based on the participants' muscular strength. This approach has been used in four studies that
527 focused on a comparison of strongman and traditional lifts, with the results assisting in
528 improving the understanding of how strongman exercises may be best, if at all, included in the
529 strength and conditioning programmes of non-strongman athletes (Renals, et al., 2018;
530 Winwood, et al., 2014a, 2015a, 2015b). However, basing loads on an athlete's 1RM does not
531 mimic actual strongman competition, whereby athletes of a given gender and body mass
532 category compete with the same absolute loads for each exercise. Utilising such competition
533 loading approach in strongman performance research may be of major interest to strongman
534 coaches and athletes as it provides insight into the most important factors influencing
535 strongman competition performance.

536 It is also apparent that no strongman biomechanical study to date has assessed an
537 exercise over a range of loads as may be experienced during training and as is standard practice
538 for examining force-velocity-power relationships in traditional resistance training exercises
539 (Blatnik et al., 2014; Rahmani, Viale, Dalleau, & Lacour, 2001; Sanchez-Medina, Gonzalez-

540 Badillo, Perez, & Pallares, 2013). Both strongman coaches and athletes, and strength and
541 conditioning coaches of non-strongman athletes would benefit from such analyses as it may
542 assist in the prescription of loading during a training session or phases of a periodisation
543 training programme where specific performance outcomes are desired.

544 Limited detail on the warm up protocol undertaken by participants was provided in
545 articles reviewed. Few articles explicitly stated whether an athlete self-directed or a warm up
546 routine developed by the researcher was used, making it difficult for the reader to determine
547 the suitability of the methods selected. It could be expected that altering the usual warm up
548 protocol of an experienced athlete by enforcing a researcher designed warm up routine may
549 affect the athlete's performance during testing. Future studies should provide greater detail on
550 the warm up protocol used, and where experienced strongman athletes are included should use
551 an athlete self-directed warm up routine, with all warm up elements documented by the
552 supervising researchers. There is also no research that has quantified the effect different warm
553 up approaches may have on strongman performance and biomechanics. Therefore, it would
554 also be useful for researchers interested in strongman performance to compare the effects of
555 different warm up approaches (including the potential use of post-activation potentiation) on
556 performance in simulated strongman competitions to determine what may constitute optimal
557 warm up strategies for the sport.

558

559 ***Biomechanical Analysis:***

560 The majority of the articles reviewed used 2D kinematic analysis to estimate sagittal plane
561 temporal measures, athlete linear kinematics and joint/segment angles. The reliance on 2D
562 kinematic analysis of these strongman exercises is a potential major limitation of this research,
563 whereby three-dimensional (3D) motion capture is considered the gold standard of describing
564 athlete and object kinematics. Escamilla et al. (2000) compared 2D versus 3D kinematic

565 analysis for athletes performing the conventional and sumo deadlift. Greater differences
566 between joint/segment angles obtained using 2D versus 3D kinematic analyses were seen for
567 the sumo deadlift than the conventional deadlift. The study suggested that these differences
568 could be attributed to the multi-planar movement of the lower body in the sumo deadlift, which
569 requires a wider stance and greater angle at which the feet are turned out compared to the
570 conventional deadlift. Such results indicated that 2D kinematic analysis shows strong
571 correlation with 3D kinematic analysis for knee, thigh and hip angular motion which is
572 primarily performed in the sagittal plane only (such as the conventional deadlift). However,
573 measurement errors are to be expected when performing 2D kinematic analysis on multi-planar
574 movements in which some of the movement occurs at an angle that is not perpendicular to the
575 field of view of the camera, as is often seen in many strongman exercises such as truck pull,
576 tyre flip and weighted carries such as the farmers and yoke walk. Schurr, Marshall, Resch, and
577 Saliba (2017) has also shown that 2D kinematic analysis is comparable to 3D motion capture
578 when evaluating ankle, hip, knee and trunk angles in the sagittal plane during a single leg squat.
579 There was however, no significant correlation between the two methods at any of the joints in
580 the frontal plane except for a poor correlation at the knee. The discrepancies in the frontal plane
581 were suggested to be attributed to the possible rotation of the ankle, hip and knee joints
582 throughout the movement, as well as the high relative error of these joint motions that reflects
583 the limited range of motion of these joints in the frontal compared to the sagittal plane.

584 Although McGill, et al. (2009) successfully collected 3D motion data of athletes
585 performing a number of strongman exercises, the focus was on the lower back and required
586 data collection equipment to be attached to the posterior of the body only. While the use of a
587 similar gold standard approach such as 3D optical motion capture may provide a greater quality
588 of biomechanical measurements, especially for multi-planar movements that are not
589 perpendicular to the camera's field of view as occurs relatively often in a number of strongman

590 exercises, several difficulties in the use of this method may be experienced when applied to
591 strongman exercises. Three-dimensional optical motion capture typically requires the
592 placement of around 50 markers on various anatomical locations and planes of body segments
593 to capture accurate translational and rotational motion (Guerra-Filho, 2005). Strongman
594 exercises often require large, heavy, and awkward to position/lift implements (such as logs and
595 stones) to be lifted over large portions of the body's anterior surface, thus it would appear
596 difficult to successfully secure reflective markers to the required anatomical locations of an
597 athlete's body whilst ensuring the markers would not be obscured or displaced when
598 performing these exercises.

599 Recent developments in inertial measurement unit (IMU) based motion capture systems
600 may provide a more feasible means of collecting 3D data than traditional 3D optical motion
601 capture techniques (Blair, Duthie, Robertson, Hopkins, & Ball, 2018). Inertial measurement
602 unit motion capture systems utilise a network of sensors located at various locations on the
603 body, with the sensors secured either on the skin surface or on top of or beneath clothing. The
604 development of such systems has seen various methods used for calibration, thus the versatility
605 of locating the sensors on the body provides the potential to overcome issues seen when using
606 traditional 3D motion capture systems (Filippeschi et al., 2017). Future studies may consider
607 the use of IMU systems to improve the quality and breadth of motion data collected, with such
608 an approach likely to be able to be utilised in both competition and training settings.

609 Force-velocity-power profiles of the barbell or the combined body-barbell system are
610 becoming more commonly used to prescribe training load, and assess and/or predict the
611 performance of an athlete (Argus, Gill, Keogh, & Hopkins, 2011; Giroux, Rabita, Chollet, &
612 Guilhem, 2016; Pearson, Cronin, Hume, & Slyfield, 2009; Picerno et al., 2016; Swinton,
613 Stewart, Agouris, Keogh, & Lloyd, 2011). Two of the articles included in the current review
614 obtained measurements of mean implement velocities, and mean force and power production

615 during the strongman log lift (Renals, et al., 2018; Winwood, et al., 2015b). Presenting these
616 measurements as a function of time or load may be of particular interest to strongman coaches
617 and athletes, and strength and conditioning coaches where force-velocity-power training
618 principles are considered. Future research may investigate the use of force-velocity-power
619 profiling as a tool for prescribing training strategies and predicting the success of a strongman
620 lift.

621 Standard EMG protocol procedures were generally followed in the two strongman
622 studies that assessed muscle activity, however the inherent challenges associated with using
623 EMG data to represent muscle activity must be acknowledged. These issues have generally
624 been attributed to the noise generated at the skin-electrode interface due to the relative
625 movement between the electrode, skin and muscle, the noise generated by electromagnetic
626 radiation from nearby electrical appliances, and internal cross talk detected from surrounding
627 muscles (Chowdhury et al., 2013; Vigotsky, Halperin, Lehman, Trajano, & Vieira, 2018).
628 Quantifying relative muscle activation also has a number of challenges, with normalisation to
629 the EMG signal produced during MVC readings still most commonly utilised. There are
630 however issues with normalising to MVC, especially when it is observed that one of the articles
631 reviewed had muscle activity readings for several muscles greater than 100% of the athlete's
632 pre-test MVC (McGill, et al., 2009). Ball and Scurr (2010) compared repeated (across multiple
633 days and weeks) EMG activity measurements of the triceps surae muscles whilst performing a
634 variety of exercises including the squat jump, 20 m sprint, isometric heel raise and isokinetic
635 plantar flexion. It was theorised that these exercises may provide a means of EMG
636 normalisation reference values for the triceps surae muscles. While EMG activity
637 measurements of all triceps surae muscles were reliable when performing the squat jump over
638 multiple days and weeks, measurements taken when performing the 20 m sprint, isometric heel
639 raise and isokinetic plantar flexion displayed less reliability, with reliability dependant on the

640 duration between retests and the muscle being measured. Although the challenges associated
641 with EMG readings are often acknowledged by researchers and a number of techniques have
642 been developed to reduce the likelihood of misinterpretation of data (Chowdhury, et al., 2013),
643 there are currently few practical alternative methods of acquiring and normalising muscle
644 activity data.

645 For a body to displace a load, a muscular torque exceeding the load torque must be
646 produced. The muscular torque can be defined as the product of force produced by the muscles
647 spanning the joint and their respective muscular moment arm lengths, and the load torque can
648 be defined as the product of the load force and the load moment arm length. Thus, the limb
649 length and girth of the segment contribute substantially to the resistance moment arm length,
650 muscular force produced and performance outcome of the exercise. Of the articles reviewed,
651 only one study measured participant body composition and anthropometry, with the
652 measurements obtained at one point of time from non-strongman (rugby) athletes who
653 performed a range of strongman exercises (Winwood, et al., 2012). Although the study found
654 large to very large correlations between overall strongman competition performance and many
655 anthropometric measures, measurements of limb lengths were not included in the analysis, thus
656 presenting a potential gap in the research methodology.

657 A number of anthropometric measures have been shown to be related to the technique
658 utilised (Musser, Garhammer, Rozenek, Crusemeyer, & Vargas, 2014) and performance
659 outcomes (Fry et al., 2006; Keogh, Hume, Mellow, & Pearson, 2005) of various strength based
660 exercises including the bench press, clean and jerk, snatch and squat. Although Winwood, et
661 al. (2012) investigated the correlations between a number of simple anthropometric measures
662 to the performance of athletes undertaking strongman exercises in a simulated competition, no
663 study to date has assessed how anthropometric measures influence the kinematics, kinetics or
664 muscle activity patterns of any strongman exercise. Such studies have however been conducted

665 for the snatch weightlifting event, whereby a number of anthropometric measures were found
666 to correlate to bar trajectory in elite female weightlifters (Musser, et al., 2014). Lower limb
667 length showed strong correlation to horizontal bar displacement during the first pull phase of
668 the snatch ($r = -0.93$) in female 75 kg body mass class athletes, while thigh and lower limb
669 length showed strong correlation to horizontal bar displacement during the second pull phase
670 (thigh: $r = -0.99$, lower limb: $r = -0.94$) in female 53 kg body mass class athletes (Musser, et
671 al., 2014). Various body segment ratios also showed strong correlation to horizontal bar
672 displacement across the body mass classes (Musser, et al., 2014). The exploration of the effect
673 of anthropometrics (including limb lengths) on strongman biomechanics and the resultant
674 performance measure of an athlete may be particularly interesting in strongman exercises due
675 to the apparent variation in techniques used by strongman athletes of varying anthropometric
676 characteristics. These data may be used by strongman coaches when teaching and improving
677 the technique of an athlete so to enhance performance and prevent injury, while also being of
678 interest to strength and conditioning coaches who may wish to prescribe such exercises to their
679 non-strongman athletes.

680 **Conclusion:**

681 The articles reviewed included the biomechanical analysis of eight different strongman
682 exercises, with the farmers walk being the most commonly studied exercise as it appeared in
683 five of the ten studies. The majority of the articles reviewed were more applicable to strength
684 and conditioning coaches looking to implement strongman exercises into the training
685 programmes of non-strongman athletes than to strongman athletes and coaches looking to
686 improve strongman competition performance. Although the population size and training
687 experience of participants varied between the studies reviewed, all studies consisted of male
688 participants of a largely similar lower level competitive standard, age and body mass. All
689 studies reviewed were of a cross sectional observational study design and consisted of a warm
690 up and testing component. The biomechanical measurements collected throughout the testing
691 components could be categorised into six primary areas, however due to the general awkward
692 nature of strongman exercises the methods used to collect biomechanical measurements were
693 often constrained to 2D motion capture and/or force plate analysis.

694 It is recommended future research in the field of strongman biomechanics should:
695 assess under/un-researched strongman exercises; include a greater number of experienced
696 strongman athletes (including female and lighter weight males); compare biomechanical
697 measures between strongman athletes of different performance standards; consider the
698 collection of biomechanical data over a range of loading conditions (e.g. competition loads);
699 utilise advanced measurement technologies (e.g. 3D and/or IMU motion capture) for the
700 collection of data; consider how anthropometric measures (such as limb length) affect the
701 biomechanics and performance of an athlete. With improvements in the research methodology
702 of future strongman biomechanics studies, strength and conditioning coaches, and strongman
703 athletes and coaches will be able to better understand; how strongman exercises may be used
704 in wider strength and conditioning or injury rehabilitation practice, and the technique required

705 to perform these exercises in a way that ensures the greatest performance outcome while
706 minimising the risk of injury.
707

708 **Acknowledgements:**

709 The Authors wish to acknowledge Shiqi Thng for her contribution during the screening of
710 literature and quality/risk of bias assessment processes.

711

712

713 **Funding details:**

714 This research is supported by an Australian Government Research Training Program
715 Scholarship to the primary author.

716

717

718 **Disclosure statement:**

719 The Authors declare they have no conflicts of interest pertinent to the content of the review.

720

721

722 **References**

- 723 Argus, C. K., Gill, N. D., Keogh, J. W. L., & Hopkins, W. G. (2011). Assessing lower-body peak power in elite
724 rugby-union players. *Journal of Strength and Conditioning Research*, 25(6), 1616-1621. doi:
725 10.1519/JSC.0b013e3181ddfabc
- 726 Ariëns, G. A. M., van Mechelen, W., Bongers, P. M., Bouter, L. M., & van der Wal, G. (2000). Physical risk
727 factors for neck pain. *Scandinavian Journal of Work, Environment & Health*, 26(1), 7-19. doi:
728 10.5271/sjweh.504
- 729 Ball, N., & Scurr, J. (2010). An assessment of the reliability and standardisation of tests used to elicit reference
730 muscular actions for electromyographical normalisation. *Journal of Electromyography and Kinesiology*,
731 20(1), 81-88. doi: 10.1016/j.jelekin.2008.09.004
- 732 Berning, J. M., Adams, K. J., Climstein, M., & Stamford, B. A. (2007). Metabolic demands of "junkyard" training:
733 pushing and pulling a motor vehicle. *Journal of Strength and Conditioning Research*, 21(3), 853-856.
734 doi: 10.1519/R-18335.1
- 735 Blair, S., Duthie, G., Robertson, S., Hopkins, W. G., & Ball, K. (2018). Concurrent validation of an inertial
736 measurement system to quantify kicking biomechanics in four football codes. *Journal of Biomechanics*,
737 73, 24-32. doi: 10.1016/j.jbiomech.2018.03.031
- 738 Blatnik, J. A., Goodman, C. L., Capps, C. R., Awelewa, O. O., Triplett, T. N., Erickson, T. M., & McBride, J. M.
739 (2014). Effect of load on peak power of the bar, body and system during the deadlift. *Journal of Sports*
740 *Science and Medicine*, 13(3), 511-515. Retrieved from <https://www.jssm.org>
- 741 Chowdhury, R. H., Reaz, M. B., Ali, M. A., Bakar, A. A., Chellappan, K., & Chang, T. G. (2013). Surface
742 electromyography signal processing and classification techniques. *Sensors*, 13(9), 12431-12466. doi:
743 10.3390/s130912431
- 744 Cross, M. R., Tinwala, F., Lenetsky, S., Samozino, P., Brughelli, M., & Morin, J. B. (2017). Determining friction
745 and effective loading for sled sprinting. *Journal of Sports Sciences*, 35(22), 2198-2203. doi:
746 10.1080/02640414.2016.1261178
- 747 Davids, E. L., & Roman, N. V. (2014). A systematic review of the relationship between parenting styles and
748 children's physical activity. *African Journal for Physical Health Education, Recreation and Dance*,
749 20(Supplement 2), 228-246. Retrieved from <https://journals.co.za/content/journal/ajpherd>
- 750 DuRant, R. H. (1994). Checklist for the evaluation of research articles. *Journal of Adolescent Health*, 15(1), 4-8.
751 doi: 10.1016/1054-139X(94)90381-6

752 Escamilla, R. F., Francisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., . . . Andrews, J.
753 R. (2000). A three-dimensional biomechanical analysis of sumo and conventional style deadlifts.
754 *Medicine and Science in Sports and Exercise*, 32(7), 1265-1275. doi: 10.1097/00005768-200007000-
755 00013

756 Filippeschi, A., Schmitz, N., Miezal, M., Bleser, G., Ruffaldi, E., & Stricker, D. (2017). Survey of motion tracking
757 methods based on inertial sensors: a focus on upper limb human motion. *Sensors*, 17(6). doi:
758 10.3390/s17061257

759 Fry, A. C., Ciroslan, D., Fry, M. D., LeRoux, C. D., Schilling, B. K., & Chiu, L. Z. (2006). Anthropometric and
760 performance variables discriminating elite American junior men weightlifters. *Journal of Strength and*
761 *Conditioning Research*, 20(4), 861-866. doi: 10.1519/R-18355.1

762 Gaviglio, C. M., Osborne, M., Kelly, V. G., Kilduff, L. P., & Cook, C. J. (2015). Salivary testosterone and cortisol
763 responses to four different rugby training exercise protocols. *European Journal of Sport Science*, 15(6),
764 497-504. doi: 10.1080/17461391.2015.1017012

765 Ghigiarelli, J. J., Sell, K. M., Raddock, J. M., & Taveras, K. (2013). Effects of strongman training on salivary
766 testosterone levels in a sample of trained men. *Journal of Strength and Conditioning Research*, 27(3),
767 738-747. doi: 10.1519/JSC.0b013e3182578115

768 Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2016). Optimal balance between force and velocity differs
769 among world-class athletes. *Journal of Applied Biomechanics*, 32(1), 59-68. doi: 10.1123/jab.2015-0070

770 Guerra-Filho, G. (2005). Optical motion capture: theory and implementation. *IEEE Revista Iberoamericana de*
771 *Tecnologias del Aprendizaje*, 12(2), 61-90. Retrieved from
772 <https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=6245520>

773 Gyorkos, T. W., Tannenbaum, T. N., Abrahamowicz, M., Oxman, A. D., Scott, E. A., Millson, M. E., . . . Best,
774 A. (1994). An approach to the development of practice guidelines for community health interventions.
775 *Canadian Journal of Public Health*, 85, S8-13. Retrieved from <https://journal.cpha.ca/index.php/cjph>

776 Hall, D. E., & Moreland, J. C. (2001). Fundamentals of rolling resistance. *Rubber Chemistry and Technology*,
777 74(3), 525-539. doi: 10.5254/1.3547650

778 Harris, N. K., Woulfe, C. J., Wood, M. R., Dulson, D. K., Gluchowski, A. K., & Keogh, J. W. L. (2016). Acute
779 physiological responses to strongman training compared to traditional strength training. *Journal of*
780 *Strength and Conditioning Research*, 30(5), 1397-1408. doi: 10.1519/JSC.0000000000001217

781 Havelka, J. (2004). *Personal best: How to train for the sport of strongman*. Portland, OR: Moxie Publishing
782 Company.

783 Keogh, J. W. L., Hume, P., Mellow, P., & Pearson, S. (2005). The use of anthropometric variables to predict
784 bench press and squat strength in well-trained strength athletes. *International Symposium on*
785 *Biomechanics in Sports: Conference Proceedings Archive*, 126-129. Retrieved from [https://ojs.uni-](https://ojs.uni-konstanz.de/cpa)
786 [konstanz.de/cpa](https://ojs.uni-konstanz.de/cpa)

787 Keogh, J. W. L., Kattan, A., Logan, S., Bensley, J., Muller, C., & Powell, L. (2014). A preliminary kinematic gait
788 analysis of a strongman event: the farmers walk. *Sports*, 2(1), 24-33. doi: 10.3390/sports2010024

789 Keogh, J. W. L., Newlands, C., Blewett, S., Payne, A. L., & Chun-Er, L. (2010a). A kinematic analysis of a
790 strongman-type event: the heavy sprint-style sled pull. *Journal of Strength and Conditioning Research*,
791 24(11), 3088-3097. doi: 10.1519/JSC.0b013e3181b62c2f

792 Keogh, J. W. L., Payne, A. L., Anderson, B. B., & Atkins, P. J. (2010b). A brief description of the biomechanics
793 and physiology of a strongman event: the tire flip. *Journal of Strength and Conditioning Research*, 24(5),
794 1223-1228. doi: 10.1519/JSC.0b013e3181cc61cd

795 Keogh, J. W. L., & Winwood, P. W. (2017). The epidemiology of injuries across the weight-training sports. *Sports*
796 *Medicine*, 47(3), 479-501. doi: 10.1007/s40279-016-0575-0

797 Ma, S., & Zahalak, G. (1991). A distribution model of energetics in skeletal muscle. *Journal of Biomechanics*,
798 24(1), 21-35. doi: 10.1016/0021-9290(91)90323-f

799 McGill, S. M., McDermott, A., & Fenwick, C. M. (2009). Comparison of different strongman events: trunk muscle
800 activation and lumbar spine motion, load, and stiffness. *Journal of Strength and Conditioning Research*,
801 23(4), 1148-1161. doi: 10.1519/JSC.0b013e318198f8f7

802 McGill, S. M., & Norman, R. W. (1985). Dynamically and statically determined low back moments during lifting.
803 *Clinical Biomechanics*, 1(2), 116. doi: 10.1016/0268-0033(86)90125-7

804 McManus, A., O'Driscoll, J., Coleman, D. A., & Wiles, J. (2016a). Strongman training (part 2): needs analysis
805 and integration into strength & conditioning programming. *Professional Strength & Conditioning*, 44,
806 7-15. Retrieved from <https://www.ukzca.org.uk/home>

807 McManus, A., Wiles, J., Coleman, D. A., & O'Driscoll, J. (2016b). Strongman training (part 1): a rationale for its
808 inclusion in strength & conditioning. *Professional Strength & Conditioning*, 43, 7-18. Retrieved from
809 <https://www.ukzca.org.uk/home>

- 810 Musser, L. J., Garhammer, J., Rozenek, R., Crussemeyer, J. A., & Vargas, E. M. (2014). Anthropometry and
811 barbell trajectory in the snatch lift for elite women weightlifters. *Journal of Strength and Conditioning*
812 *Research*, 28(6), 1636-1648. doi: 10.1519/JSC.0000000000000450
- 813 Pearson, S. N., Cronin, J. B., Hume, P. A., & Slyfield, D. (2009). Kinematics and kinetics of the bench-press and
814 bench-pull exercises in a strength-trained sporting population. *Sports Biomechanics*, 8(3), 245-254. doi:
815 10.1080/14763140903229484
- 816 Picerno, P., Iannetta, D., Comotto, S., Donati, M., Pecoraro, F., Zok, M., . . . Piacentini, M. F. (2016). 1RM
817 prediction: a novel methodology based on the force-velocity and load-velocity relationships. *European*
818 *Journal of Applied Physiology*, 116(10), 2035-2043. doi: 10.1007/s00421-016-3457-0
- 819 Rahmani, A., Viale, F., Dalleau, G., & Lacour, J. R. (2001). Force/velocity and power/velocity relationships in
820 squat exercise. *European Journal of Applied Physiology*, 84(3), 227-232. doi: 10.1007/PL00007956
- 821 Renals, L., Lake, J., Keogh, J. W. L., & Austin, K. (2018). Strongman log push press: the effect log diameter has
822 on force-time characteristics. *Journal of Strength and Conditioning Research*, 32(10), 2693-2700. doi:
823 10.1519/JSC.0000000000002764
- 824 Roman, N. V., & Frantz, J. M. (2013). The prevalence of intimate partner violence in the family: a systematic
825 review of the implications for adolescents in Africa. *Family Practice*, 30(3), 256-265. doi:
826 10.1093/fampra/cms084
- 827 Sanchez-Medina, L., Gonzalez-Badillo, J. J., Perez, C. E., & Pallares, J. G. (2013). Velocity- and power-load
828 relationships of the bench pull vs. bench press exercises. *International Journal of Sports Medicine*, 35(3),
829 209-216. doi: 10.1055/s-0033-1351252
- 830 Schurr, S. A., Marshall, A. N., Resch, J. E., & Saliba, S. A. (2017). Two-dimensional video analysis is comparable
831 to 3D motion capture in lower extremity movement assessment. *International Journal of Sports Physical*
832 *Therapy*, 12(2), 163-172. Retrieved from [https://spts.org/member-benefits-detail/enjoy-member-](https://spts.org/member-benefits-detail/enjoy-member-benefits/journals/ijspst)
833 [benefits/journals/ijspst](https://spts.org/member-benefits-detail/enjoy-member-benefits/journals/ijspst)
- 834 Shamseer, L., Moher, D., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., . . . PRISMA-P. Group. (2015).
835 Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015:
836 elaboration and explanation. *BMJ*, 350, g7647. doi: 10.1136/bmj.g7647
- 837 Stastny, P., Lehnert, M., Zaatar, A., Svoboda, Z., Xaverova, Z., & Pietraszewski, P. (2015). The gluteus medius
838 vs. thigh muscles strength ratio and their relation to electromyography amplitude during a farmer's walk
839 exercise. *Journal of Human Kinetics*, 45, 157-165. doi: 10.1515/hukin-2015-0016

- 840 Swinton, P. A., Stewart, A., Agouris, I., Keogh, J. W. L., & Lloyd, R. (2011). A biomechanical analysis of straight
841 and hexagonal barbell deadlifts using submaximal loads. *Journal of Strength and Conditioning Research*,
842 25(7), 2000-2009. doi: 10.1519/JSC.0b013e3181e73f87
- 843 van der Windt, D. A., Thomas, E., Pope, D. P., de Winter, A. F., Macfarlane, G. J., Bouter, L. M., & Silman, A.
844 J. (2000). Occupational risk factors for shoulder pain: a systematic review. *Occupational and*
845 *Environmental Medicine*, 57(7), 433-442. doi: 10.1136/oem.57.7.433
- 846 Vandembroucke, J. P., von Elm, E., Altman, D. G., Gotzsche, P. C., Mulrow, C. D., Pocock, S. J., . . . STROBE
847 Initiative. (2007). Strengthening the reporting of observational studies in epidemiology (STROBE):
848 explanation and elaboration. *PLoS Med*, 4(10), e297. doi: 10.1371/journal.pmed.0040297
- 849 Vigotsky, A. D., Halperin, I., Lehman, G. J., Trajano, G. S., & Vieira, T. M. (2018). Interpreting signal amplitudes
850 in surface electromyography studies in sport and rehabilitation sciences. *Frontiers in Physiology*, 8, 985.
851 doi: 10.3389/fphys.2017.00985
- 852 Waller, M., Piper, T., & Townsend, R. (2003). Strongman events and strength and conditioning programs.
853 *Strength and Conditioning Journal*, 25(5), 44-52. doi: 10.1519/00126548-200310000-00008
- 854 Winwood, P. W., Cronin, J. B., Brown, S. R., & Keogh, J. W. L. (2014a). A biomechanical analysis of the farmers
855 walk, and comparison with the deadlift and unloaded walk. *International Journal of Sports Science &*
856 *Coaching*, 9(5), 1127-1143. doi: 10.1260/1747-9541.9.5.1127
- 857 Winwood, P. W., Cronin, J. B., Brown, S. R., & Keogh, J. W. L. (2015a). A biomechanical analysis of the heavy
858 sprint-style sled pull and comparison with the back squat. *International Journal of Sports Science &*
859 *Coaching*, 10(5), 851-868. doi: 10.1260/1747-9541.10.5.851
- 860 Winwood, P. W., Cronin, J. B., Brown, S. R., & Keogh, J. W. L. (2015b). A biomechanical analysis of the
861 strongman log lift and comparison with weightlifting's clean and jerk. *International Journal of Sports*
862 *Science & Coaching*, 10(5), 869-886. doi: 10.1260/1747-9541.10.5.869
- 863 Winwood, P. W., Cronin, J. B., Keogh, J. W. L., Dudson, M. K., & Gill, N. D. (2014b). How coaches use
864 strongman implements in strength and conditioning practice. *International Journal of Sports Science &*
865 *Coaching*, 9(5), 1107-1125. doi: 10.1260/1747-9541.9.5.1107
- 866 Winwood, P. W., Cronin, J. B., Posthumus, L. R., Finlayson, S. J., Gill, N. D., & Keogh, J. W. L. (2015c).
867 Strongman vs. traditional resistance training effects on muscular function and performance. *Journal of*
868 *Strength and Conditioning Research*, 29(2), 429-439. doi: 10.1519/JSC.0000000000000629

869 Winwood, P. W., Dudson, M. K., Wilson, D., McLaren-Harrison, J. K. H., Redjkins, V., Pritchard, H. J., & Keogh,
870 J. W. L. (2018). Tapering practices of strongman athletes. *Journal of Strength and Conditioning*
871 *Research*, 32(5), 1181-1196. doi: 10.1519/JSC.0000000000002453

872 Winwood, P. W., Hume, P. A., Cronin, J. B., & Keogh, J. W. L. (2014c). Retrospective injury epidemiology of
873 strongman athletes. *Journal of Strength and Conditioning Research*, 28(1), 28-42. doi:
874 10.1519/JSC.0b013e3182986c0c

875 Winwood, P. W., Keogh, J. W. L., & Harris, N. K. (2011). The strength and conditioning practices of strongman
876 competitors. *Journal of Strength and Conditioning Research*, 25(11), 3118-3128. doi:
877 10.1519/JSC.0b013e318212daea

878 Winwood, P. W., Keogh, J. W. L., & Harris, N. K. (2012). Interrelationships between strength, anthropometrics,
879 and strongman performance in novice strongman athletes. *Journal of Strength and Conditioning*
880 *Research*, 26(2), 513-522. doi: 10.1519/JSC.0b013e318220db1a

881 Wong, W. C., Cheung, C. S., & Hart, G. J. (2008). Development of a quality assessment tool for systematic
882 reviews of observational studies (QATSO) of HIV prevalence in men having sex with men and associated
883 risk behaviours. *Emerging Themes in Epidemiology*, 5, 23. doi: 10.1186/1742-7622-5-23

884 Woulfe, C. J., Harris, N. K., Keogh, J. W. L., & Wood, M. R. (2014). The physiology of strongman training.
885 *Strength and Conditioning Journal*, 36(6), 84-95. doi: 10.1519/Ssc.0000000000000104

886 Zemke, B., & Wright, G. (2011). The use of strongman type implements and training to increase sport performance
887 in collegiate athletes. *Strength and Conditioning Journal*, 33(4), 1-7. doi:
888 10.1519/SSC.0b013e3182221f96

889