

Manuscript title

Validity, reliability, and normative data on calf muscle function in rugby union players from the Calf

Raise application

Running head

Calf muscle function in rugby union

XXXX

Tables: 6 tables

Figures: 4 figures

Twitter: Calf power and endurance was tested in 120 rugby players. Super Rugby more powerful than Club and Provincial. Forwards more powerful than backs, but lower endurance. Calf Raise app is valid and reliable.

1 **Benchmarking calf muscle function in rugby union players using the Calf Raise application**

2
3 We examined the validity and reliability of biomechanical outcomes extracted using the Calf Raise
4 application of three calf muscle tests. We then established normative calf muscle function values for
5 male rugby union players accounting for rugby-related factors (position, level) alone and together with
6 clinical factors (age, leg dominance, BMI, previous injury). In total, 120 athletes performed three single-
7 leg calf muscle tests. Twenty athletes participated in application validation; 18 in test-retest reliability;
8 and all in establishing normative equations. Validity of application outcomes against 3D motion and
9 force plate data was good-to-excellent ($CV \leq 6.6\%$, $ICC \geq 0.84$). Test-retest reliability was good across
10 outcomes following familiarisation ($CV < 10\%$, $ICC \geq 0.83$). Forwards produced superior power than
11 backs during the bodyweight (59 W, $p=0.007$) and weighted (73 W, $p<0.001$) power tests. Playing level
12 influenced power outcomes ($p<0.009$). Super Rugby players were more powerful than Club (both power
13 tests), Provincial (both power tests), and International (bodyweight power). Backs completed more
14 repetitions (3 repetitions, $p=0.001$) and positive displacement (30 cm, $p=0.001$) than forwards during
15 endurance testing. When accounting for clinical factors, BMI, age, and previous injury explained some
16 of the differences observed between positions and levels. This study provides initial benchmark values
17 of calf muscle function in rugby union.

18
19 **Keywords:** Biomechanics, football, physical endurance, sports, muscle strength, triceps surae

20 INTRODUCTION

21

22 Rugby union is a team-contact sport played globally across ages, genders, and ethnicities. The sport is
23 best known for its combination of physicality, levels of high-intensity, and continuous periods of play.¹
24 Fifteen players per team take the field during games, with players assuming different positions that
25 require unique physical, physiological, and tactical abilities. **Research involving rugby union players**
26 **highlight that** playing level and position are linked with different attributes and demands;^{2,3} for instance,
27 players with a greater body mass tend to display superior strength, but slower running speeds, than those
28 with a lower body mass. **In elite players**, inside and outside backs on average cover a significantly
29 greater **total** (6127 vs 5581 m) and high-intensity (448 vs 298 m) **distance** than tight and loose forwards
30 during match play.³ Differences between positions and levels likely result from numerous factors,
31 including variations in skills needed, experience, playing and training environments, training loads, and
32 match intensity.

33

34 Lower-extremity soft tissue injuries are common in rugby union.⁴ A retrospective cohort study assessing
35 rugby-related injury **claims identified** that 76% of reported cases were soft-tissue injuries, with 21% of
36 these injuries being to the lower extremity.⁴ Triceps surae (or calf) muscle⁵ and Achilles tendon^{6,7}
37 injuries are of particular concern in rugby union due to their high recurrence rates, severity based on
38 time needed to return to sport, and documented ruptures in rugby union athletes despite “normal” tendon
39 health on ultrasound imaging.^{8,9} To date, there is limited research on what constitutes “normal” calf
40 muscle function in rugby union athletes, with prior research indicating that age,¹⁰ leg dominance,¹¹ body
41 mass index (BMI),¹⁰ and previous injury¹² can influence calf muscle function. Normative data on calf
42 muscle function specific to rugby union players could help guide rehabilitation, injury prevention
43 efforts, and training strategies to improve performance.

44

45 The traditional concentric-eccentric endurance calf raise test (CRT) is used in research and clinical
46 practice to measure calf muscle endurance.¹³ However, assessing more than the endurance capacity of
47 the calf muscles in practice is recommended.¹⁴ **In presence of an Achilles tendinopathy, both concentric-**

48 eccentric calf muscle endurance and eccentric-concentric calf muscle power are reduced.¹⁵ Lower-body
49 power is an important characteristic in team sport athletes and is able to differentiate between higher
50 and lower-level rugby union players.¹⁶ Other than to inform rehabilitation and injury prevention efforts,
51 power assessments can be used to inform strength and conditioning programmes to optimise player
52 development¹⁷ and assist in monitoring player status in-season.¹⁸

53

54 The use of mobile applications in sport and exercise science is prevalent, with over 60% of surveyed
55 practitioners in the industry reporting using mobile applications to collect data.¹⁹ These mobile
56 applications provide practitioners and athletes with an appealing data collection alternative to
57 laboratory-based systems at a lower financial, time, and space cost.²⁰ The Calf Raise application (CR_{app})
58 for Apple (iOS) users was developed to facilitate the objective quantification of calf muscle function in
59 clinical or field settings using a portable tool able to replicate laboratory-based metrics. The CR_{app}
60 applies computer-vision algorithms to a video recording to track the displacement of a circular marker
61 placed on the foot of an individual. This algorithm has been shown valid and reliable for tracking barbell
62 motion during weightlifting,²¹ and hence offers an appealing solution for extracting biomechanical
63 outcomes relating to calf muscle function in athletes outside of research laboratories. It is essential that
64 tools used in clinical settings provide valid and reliable outcomes.²² However, systematic reviews of
65 mobile applications used in health²³ and sport²⁰ both point to the lack of validity and reliability studies
66 to support their evidence-based use. Thus, it was deemed important to confirm the validity and
67 reliability of the tracking algorithms used in the CR_{app} for the purpose of assessing calf muscle function
68 in rugby union players.

69

70 Therefore, we aimed to assess the validity and reliability of key biomechanical outcomes relating to
71 calf muscle function in male rugby union players collected using the novel CR_{app}. We then aimed to
72 establish normative values of calf muscle function for power and endurance in uninjured male rugby
73 union athletes while accounting for rugby-related factors (playing level and position) alone and together
74 with clinical factors (age, leg dominance, BMI, and previous injury). Based on the previous validation
75 work of the tracking algorithm implemented in the novel mobile application,²⁴ we hypothesised that the

76 Calf Raise application would exhibit good-to-excellent validity and reliability. In terms of normative
77 data, we anticipated forwards and higher-level (International and Super Rugby) players to be more
78 powerful than backs and lower-level (Provincial and Club) players based on prior research.^{2, 25}

79

80 MATERIALS AND METHODS

81

82 Sample size

83

84 For the validity portion of the study, a sample size of 15 participants would allow detection of an
85 intraclass correlation coefficient (ICC) of 0.90 reflecting an excellent agreement²⁶ between CR_{app} and
86 laboratory measures with an 80% power ($\beta = 0.20$) and 5% significance level ($\alpha = 0.05$). For reliability
87 with three retest occasions, 18 participants would be needed when setting the minimum acceptable
88 reliability level at ICC = 0.40 (i.e., fair reliability threshold) and desired reliability level at ICC = 0.75
89 (i.e., good reliability threshold) with an 80% power and 5% significance level. For the normative dataset
90 to allow exploration of potential differences between two playing positions (forwards, backs) and four
91 playing levels (International, Super Rugby, Provincial, and Club), 126 athletes were needed to detect a
92 moderate effect size difference (Cohen $f=0.30$) with an 80% power and 5% significance level based on
93 ANCOVA F tests using G*Power 3.1.9.7.

94

95 Participants

96

97 A Human Research Ethics Committee [XXXX] approved the research protocol that adhered to the
98 Declaration of Helsinki. All participants were informed of the risks (delayed onset muscle soreness)
99 and benefits (performance reports) of this investigation prior to signing an informed consent document.
100 The inclusion criteria required athletes to: willingly provide informed consent; be New Zealand Rugby
101 Union registered players currently playing rugby; be able to complete all three calf muscle tests; have
102 no current Achilles or calf muscle-tendon unit injuries; have no recent (<3 months) injuries to the lower
103 extremity; and be cleared by their medical team to participate. Provincial, Super Rugby, and

104 International players were involved with the Mitre 10 Cup competition, Super Rugby Aotearoa
105 competition, and International Test matches, respectively. Club players were in the development squads
106 of provincial teams or players in premiership teams in New Zealand.

107

108 In total, 130 male rugby union athletes from eight different rugby union teams were recruited through
109 word-of-mouth and email invitations and agreed to participate, achieving sample size requirements for
110 the normative dataset. Most teams were tested within a 2-month period. Ten athletes were excluded on
111 the day of testing due to current or recent injury, resulting in 120 athletes completing the calf muscle
112 testing procedures. Albeit lower than the targeted sample size of 126 athletes, this sample size of 120
113 athletes still permitted to detect a moderate difference (Cohen $f=0.31$ versus $f=0.30$) with an 80% power
114 and 5% significance level. A subset of these athletes ($n=20$) agreed to participate in the validity portion
115 of the study, which required them to attend one session in a biomechanics laboratory. A separate subset
116 ($n=23$) agreed to participate in the test-retest reliability study, which required them to complete two
117 additional testing sessions spread seven days apart. The reliability sessions were conducted at the same
118 time of day to limit diurnal fluctuations in performance. Participants were encouraged to replicate their
119 sleep, hydration, dietary, and training patterns between weeks. Five athletes sustained injuries or were
120 unavailable for all retest occasions and were excluded from the reliability dataset ($n=18$ total).
121 Characteristics of the players involved in the validity and reliability studies are provided in Table 1,
122 and those of players included in the normative dataset are presented in Table 2.

123

124 ***TABLE 1***

125

126 ***TABLE 2***

127

128 Procedures

129

130 Upon arrival for testing, participants signed the informed consent document and completed a short
131 baseline questionnaire to collect clinically-relevant factors. These factors included age, leg dominance

132 (i.e., side used to kick a ball), and previous injury to the calf muscle tendon unit requiring medical
133 attention. Body height to the nearest cm and mass to the nearest 0.01 kg were recorded barefoot using
134 a stadiometer (seca model 0123) and scale (seca Model ESE813), respectively, from which BMI was
135 computed. Black circular adhesive stickers (24 mm diameter) were placed onto white ones (32 mm
136 diameter) to track test performance using the CR_{app},²⁷ which uses a previously validated computer-
137 vision algorithm that enables image-processing features to track the 2D path of selected objects from
138 video footage.²⁴ More specifically, a scalable circle of known diameter is positioned around the circular
139 adhesive marker in the first video frame to calibrate the application. The computer-vision algorithm
140 subsequently tracks the motion of the selected marker throughout the video footage. Although only the
141 24 mm sticker was tracked, the two stickers were used to ensure colour contrast across skin tones
142 (Figure 1). The markers were affixed to the skin of participants beneath the lateral malleolus in-line
143 with the calcaneus. Participants were then required to perform three single-leg tests barefoot on a 20-
144 cm high box on both right and left legs, with the forefoot placed on the edge of the box. Side was
145 randomised, but test sequence was kept consistent and involved performing an: 1) eccentric-concentric
146 bodyweight power test; 2) eccentric-concentric weighted power test; and 3) concentric-eccentric
147 endurance test. The protocol for each test is presented in detail below. Before each test, participants
148 were familiarised with the protocol and performed three practice repetitions under supervision. These
149 tests were based on procedures shown to have acceptable reliability (ICC 0.76 to 0.96),^{10, 15} validity in
150 Achilles tendinopathy patients¹⁵, and ability to identify meaningful differences in function.²⁸ The load
151 of 35 kg was selected for the weighted power test based on: a previous study finding that a 33 kg load
152 was sensitive to Achilles tendinopathy,¹⁵ the availability of the 35 kg external load in dumbbell form,
153 and the desire for a common benchmark load across players implementable across teams and gym
154 settings. Indeed, the tests were adapted for ease-of-implementation in rugby union settings, such as
155 using free-weights (i.e., dumbbells) rather than a weight machine for the weighted power tests and a
156 box rather than an incline for the endurance test.

157

158 ***FIGURE 1***

159

160 All testing was performed in a well-light environment on a flat hard surface. The edge of the box was
161 positioned 50 cm from a wall and a strip of tape was placed on the midline of the box to indicate where
162 participants needed to place their tested foot. An iPad (model A1822, Apple Inc., California, USA)
163 running iOS 14.1 was positioned on a stand 50 cm from the midline of the box on both the right and
164 left sides in portrait orientation to enable tracking of the marker through full range of motion. Videos
165 during testing were recorded using the CR_{app} at 60 frames per second, collected and analysed by a single
166 investigator to limit bias (XXXX). The inter-rater reliability of the Calf Raise application was assessed
167 internally. Three independent raters novice to the CR_{app} performed the analysis independently of each
168 other on 106 endurance videos and 119 bodyweight and weighted power test videos. **Inter-rater**
169 **reliability was excellent based on ICC and typical errors expressed as coefficients of variation (CV)**
170 **values for both power tests (ICC \geq 0.93, CV \leq 5% for peak power) and the endurance test (ICC \geq 0.99,**
171 **CV \leq 3% for number of repetitions, total positive displacement, and total positive work).**

172

173 For the validity portion of this study, data were collected concurrently using the CR_{app} and **both**
174 **kinematic and kinetic** laboratory equipment. Specifically, a retroreflective marker of 12.5 mm in
175 diameter was placed in the centre of the 24 mm black marker (**Figure 1**) to collect 3D motion using an
176 8-camera Oqus 700 3D motion capture system sampling at 60 Hz and the Qualisys Track Manager
177 software v.2019.3.4930 (Qualisys AB, Gothenburg, Sweden). **A step with four feet made of steel was**
178 **specifically designed to fit on top of a Kistler 9260AA6 multicomponent force plate (Kistler Group,**
179 **Winterthur, Switzerland) to record ground reaction forces during testing.** Ground reaction force data
180 were sampled at 120 Hz using a 5695B2 DAQ system (Kistler Group, Winterthur, Switzerland),
181 synchronised to the 3D motion capture, and collected within the Qualisys Track Manager.

182

183 *Eccentric-concentric bodyweight power test*

184

185 Following warm-up and familiarisation, participants completed three repetitions of the eccentric-
186 concentric bodyweight power test (**Figure 2**). Participants stood with their forefeet on the edge of the
187 box, with the tested foot on the midline. Participants were permitted index and middle fingertips support

188 from both hands on the wall at shoulder height for balance and asked to maintain the knee of their tested
189 leg straight during testing. Participants then lifted both heels as high as possible, raised the non-tested
190 foot, and went “down and up” as quickly as possible, returning their heel to the initial position.
191 Participants had ~2 seconds between repetitions, and 30 seconds rest between legs. The repetition with
192 the greatest peak power (W) during ascent was used as the primary outcome for each leg.

193

194 ***FIGURE 2***

195

196 *Eccentric-concentric weighted power test*

197

198 Following warm-up and familiarisation, the eccentric-concentric weighted power test was like the
199 previous test, except participants held a 35 kg dumbbell on their ipsilateral shoulder and were permitted
200 to place five fingertips of their opposite hand on the wall at shoulder height for balance support (**Figure**
201 **3**). A towel was placed over the shoulder to increase comfort. The repetition with the greatest peak
202 power (W) during ascent was used as the primary outcome for each leg.

203

204 ***FIGURE 3***

205

206 *Concentric-eccentric endurance test*

207

208 Following warm-up and familiarisation, participants were required to perform as many single-legged
209 concentric-eccentric calf raises as possible (**Figure 4**). Participants started standing with their forefeet
210 on the edge of the box, with the tested foot on the midline. Participants were permitted index and middle
211 fingertips support from both hands on the wall at shoulder height for balance, raised their non-tested
212 foot, and asked to maintain their knee of their tested leg straight during testing. Participants then raised
213 and lowered their heel to the beat of a 60 Hz metronome, lifting their heel as high as possible in one
214 beat and lowering it in one beat (i.e., 30 calf raise repetitions per minute). Participants were encouraged
215 to go through the full range of available motion. The test was terminated once participants were no

216 longer able to perform a single calf raise, could not maintain the beat of the metronome, demonstrated
217 compensatory movements (e.g., knee flexion, trunk lean, hip strategy), or showed marked reduction in
218 heel range of motion. Verbal encouragement was provided at regular intervals throughout testing. Two
219 minutes rest was allocated between legs. The number of repetitions (n), total positive displacement
220 (cm), and total positive work (J) were used as the primary outcomes for each leg as is commonly done
221 in the scientific literature.^{10, 29-31}

222

223 ***FIGURE 4***

224

225 **Data extraction**

226

227 The CR_{app}²⁷ tracks a circular marker placed on the foot according to validated tracking algorithms used
228 to track barbell motion.²⁴ From the vertical displacement curve, the number of repetitions (n) is
229 extracted, as is the total positive (vertical) displacement (d , in cm). Prior to data extraction, the mass of
230 individuals recorded on the day is entered to enable positive work (J) computation during the endurance
231 test as:

232

$$233 \quad \text{Work} = F_g \times d$$

234

235 where F_g is computed as mass times gravitational acceleration ($g = 9.81 \text{ m/s}^2$). Peak power (W) for the
236 two power tests is extracted from the power curve, which is generated using:

237

$$238 \quad \text{Power} = \frac{\text{Work}}{\Delta \text{time}} = \frac{F_g \times d}{\Delta \text{time}}$$

239

240 where Δtime is based on the sampling frequency (i.e., 0.0167 s). Note that the additional weight of 35
241 kg was added to the body mass when calculating power for the eccentric-concentric weighted power
242 test.

243

244 The raw data collected using the Qualisys Track Manager software were exported to the .c3d format
245 and processed using Visual3D Professional software version 2021.01.1 (C-Motion Inc., Germantown,
246 Maryland, USA). Any marker data gaps up to 6 frames were interpolated using a third order polynomial
247 fit algorithm, and a fourth order low-pass Butterworth filter with a cut-off frequency of 15 Hz was
248 applied to the force plate data. From the marker vertical position data, peak positive power was extracted
249 for the power tests and the number of repetitions, total positive displacement, and total positive work
250 were extracted for the endurance test using the same approach described for the CR_{app} data processing
251 and extraction. In addition, work and power curves were generated using the force plate vertical ground
252 reaction force and marker vertical displacement rather than using a fixed force based on the body mass
253 and external weight.

254

255 **Statistical analysis**

256

257 Descriptive statistics were computed for all dependent and independent variables. All statistical
258 analyses were performed using STATA/IC v.16.1 (StataCorp LP, TX, USA) and Microsoft Excel 2016
259 (Microsoft Corp., Redmont, WA, USA) with the significance level set at $p \leq 0.05$.

260

261 *Validity and reliability*

262 Both validity and reliability of measures were analysed using similar approaches. Two-way mixed
263 effects single measurement ICC_{1,3}, typical error (TE), and TE expressed as a coefficient of variation
264 (CV) with 95% confidence intervals [lower, upper] were calculated to quantify relative (ICC) and
265 absolute (TE and CV) reliability and concurrent validity. Relative reliability and agreement of measures
266 were considered poor, fair, and good when corresponding ICC values were < 0.40 , $0.40 - < 0.75$, and
267 ≥ 0.75 ,³² respectively, and excellent when above 0.90 .²⁶ Absolute reliability and agreement were deemed
268 acceptable when CV values were $< 10\%$;³³ otherwise, they were deemed suboptimal.

269

270 *Normative dataset*

271 Baseline characteristics of players in the normative dataset were compared between positions and levels
272 using two-way ANOVAs for continuous variables (age, mass, height, BMI) and contingency tables for
273 binomial data (dominance, previous injury) with Chi Square or Fischer exact tests. Thereafter,
274 Generalized Estimation Equation (GEE)³⁴ were used to assess the effect of position (forwards, backs)
275 and level (International, Super Rugby, Provincial, Club) on peak power from the two power tests, and
276 number of repetitions, total positive displacement, and positive work from the endurance test. We
277 selected the GEE approach as estimates consider the variation within individuals in presence of multiple
278 observations. The GEE approach provides an estimate with its 95% confidence interval [lower, upper]
279 of the average effect in a population, applying robust standard errors to account for within-individual
280 correlations.

281

282 The GEE models applied a Gaussian (normal) distribution for continuous variables (peak power, total
283 displacement, and positive work), and Poisson distribution for count (number of repetitions). All GEE
284 models clustered within-participant measures and applied an exchangeable correlation structure, which
285 assumes observations have the same amount of correlation over time.

286

287 A stepwise regression technique was applied, wherein non-significant effects were sequentially
288 removed from the model resulting in a final model containing only significant effects. The intercept and
289 coefficients from these final models were extracted to provide researchers and clinicians a means of
290 estimating outcomes from the calf muscle testing procedures under a known set of conditions. Forwards
291 and International were the defined position and level references from which all estimates were derived.
292 Two separate models were constructed. The first model contained rugby-related factors only (Model A:
293 Position + Level), whereas the second contained rugby-related and other clinically relevant factors
294 (Model B: Position + Level + BMI + Age + Previous Calf Muscle Tendon Unit Injury + Leg
295 Dominance). In presence of a significant main effect of level, pairwise comparisons of marginal linear
296 predictions and their 95% confidence intervals were extracted.

297

298 **RESULTS**

299

300 **Validity**

301

302 The comparison between CR_{app} outcomes against laboratory-based outcomes are summarised in **Table**
303 **3**. The relative validity of outcomes across all testing measures were good to excellent when comparing
304 the CR_{app} against the force plate and 3D motion capture (ICC 0.84 to 1.00). The absolute validity across
305 all testing measures were acceptable when comparing the CR_{app} against the force plate and 3D motion
306 capture also (CV<10%).

307

308 ***TABLE 3***

309

310 **Reliability**

311

312 Outcomes from the test-retest reliability study are summarised in the **Table 4**. Reliability of outcomes
313 were fair across measures between the first and second test occasion (ICC 0.67–0.75) and good between
314 the second and third test occasion (ICC 0.83–0.88). The absolute reliability between the first and second
315 session was suboptimal across measures (CV 11–15%), but acceptable between the second and third
316 session (CV<10%).

317

318 ***TABLE 4***

319

320 **Normative dataset: Baseline characteristics and calf muscle function**

321 In terms of baseline characteristics (**Table 2**), the frequency of previous muscle tendon unit injuries was
322 greater in forwards than backs (Chi-square $p<0.001$) and was influenced by level (Fisher's exact
323 $P<0.001$), with more injuries reported in International-level players (61% yes). International and Super
324 players were older than Provincial and Club ($P\leq 0.001$), as well as heavier than the other levels ($P\leq$
325 0.023), but of similar height. International players had larger BMI than Provincial and Club ($P\leq 0.018$),
326 as did forwards compared to backs ($P=0.0248$). Forwards were also taller and heavier than backs (both

327 $P<0.001$). All other baseline characteristics were similar between playing position and levels. A
328 summary of the calf muscle test outcomes by position and level is provided in **Table 5**.

329

330 ***TABLE 5***

331

332 **Normative dataset: Equations**

333 Results from the GEE analyses for Model A (rugby-related factors) and Model B (rugby-related and
334 clinically relevant factors) are presented in **Table 6**.

335

336 ***TABLE 6***

337

338 *Eccentric-concentric bodyweight power test*

339

340 In the rugby-only model, position and level significantly influenced bodyweight power (**Table 6**).
341 Forwards produced greater power than backs (72.8 W, $P<0.001$). Pairwise comparisons revealed that
342 Super Rugby athletes were more powerful than International (58.8 W, $P=0.035$), Provincial (67.6 W,
343 $P=0.010$), and Club (91.8 W, $P=0.002$). Adding the clinically relevant factors did not alter the results.

344

345 *Eccentric-concentric weighted power test*

346

347 Playing position and level significantly influenced weighted power when rugby-related factors were
348 considered in isolation (**Table 6**). Forwards produced greater power than backs (59.27 W, $P=0.017$).
349 Pairwise comparisons revealed that International and Super Rugby players were more powerful than
350 Club (77.2 W and 126.2 W, $P\leq 0.049$), with Super Rugby also more powerful than Provincial (64.1 W,
351 $P=0.047$). When adding the clinically relevant factors to the model, position was no longer significant
352 and differences between levels were attenuated, with only Super Rugby remaining significantly more

353 powerful than Club (110.1 W, $P=0.003$). Each increase in BMI unit was associated with a 13.3 W
354 increase in weighted power output ($P=0.003$) (Table 6).

355

356 *Concentric-eccentric endurance test*

357

358 When considering rugby-related factors only, backs completed a greater number of repetitions (2.7
359 repetitions) and total positive displacement (30.2 cm, both $P=0.001$) than forwards, with no significant
360 effect of level. However, the difference in the number of repetitions between positions was no longer
361 significant when adding clinically relevant factors. A history of prior calf muscle tendon-unit injury and
362 greater BMI negatively affected the number of repetitions completed. Age also influenced total
363 displacement (-2.5 cm for each 1-year change, $P=0.034$), reducing the positional difference to 27.9 cm
364 ($P=0.002$) between forwards and backs. Neither the rugby-related nor clinically relevant factors
365 influenced the positive work completed (Table 6). The coefficients indicate that rugby athletes on
366 average complete 1977.4 J during the concentric-eccentric endurance test.

367

368 **DISCUSSION AND IMPLICATIONS**

369

370 We aimed to determine the validity and reliability of biomechanical outcomes from three calf muscle
371 tests extracted using the novel CR_{app} and establish normative values of calf muscle function in uninjured
372 male rugby union athletes. As hypothesised, CR_{app} outcomes were reliable between raters assessing the
373 same videos, reliable in players between weeks after an initial familiarisation session, and valid when
374 compared to the 3D motion capture system and force plate data. As hypothesised, forwards were more
375 powerful than backs, as were Super Rugby players, notably compared against Club and Provincial
376 players. In terms of the concentric-eccentric endurance test, backs outperformed forwards, with no
377 differences between playing levels. When accounting for additional clinically relevant factors, BMI,
378 age, and previous injury explained some of the significant differences observed between positions and
379 levels. This study provides initial benchmark values of calf muscle function for uninjured rugby union
380 athletes in New Zealand. This research is an important step forward considering that previous research

381 on calf muscle function has predominantly focused on general population^{10,29} or subgroups of injured
382 individuals.^{15, 30, 31}

383

384 The relative validity of the CR_{app} outcomes against 3D motion and force plate data found here (ICC
385 0.84 to 1.00) is similar to the relative validity of outcomes from an application that tracks barbell motion
386 from weightlifting video recordings (ICC 0.838 to 0.944) using the same computer-vision algorithms.²¹
387 In terms of test-retest reliability, superior reliability from the first to the second test occasion (ICC 0.67–
388 0.75, CV 11–15%) would have been desirable, as currently did not reach the good (ICC \geq 0.75) and
389 acceptable (CV<10%) relative and absolute reliability thresholds across CR_{app} variables. Nonetheless,
390 our reliability levels between the first and second occasion are comparable to those reported elsewhere
391 using a linear position transducer to extract biomechanical data from comparable calf muscle power¹⁵
392 and endurance^{15, 35} test procedures. Given our findings of improved reliability between the second and
393 third testing occasions, a familiarisation session prior to conducting these calf muscle assessments is
394 advised to enhance reliability. Since our normative data derive from the first test occasion of individuals,
395 there is potentially greater variability in our data set than what would have been found had an initial
396 familiarisation session been conducted with teams.

397

398 Forwards produced greater amounts of power than backs during both the bodyweight and weighted
399 power tests when not accounting for BMI, with Super Rugby being generally more powerful than the
400 other levels. Previous research conducted in New Zealand reported similar findings, with forwards
401 typically being stronger and more powerful than backs and Super Rugby players being more powerful
402 than Provincial and Club.^{2,25} The addition of clinically relevant factors to our statistical model affected
403 the differences between positions and levels observed for the weighted power outcomes, with BMI
404 significantly influencing power. Specifically, position was no longer significant given that forwards had
405 superior BMI than backs linked to their greater mass. BMI also attenuated differences in weighted
406 power between levels. These results highlight how differences in anthropometric characteristics, such
407 as greater mass in forwards and higher-level players² contribute to positional and level differences in
408 performance metrics underlying their specific on-field requirements. That the Super Rugby players

409 were more powerful than the International players for the bodyweight power test might be linked to the
410 time of the competitive season players were tested. Due to player availability and testing windows, **most**
411 **of the** Super players were tested at the start of their season whereas **most of the** International players
412 were tested towards the end of their season. Without appropriate periodization and prioritising of power
413 training, *small* decreases in lower body jump squat power take place over the competitive season.²⁵
414 However, increases in explosive hack squat power over a full season has also been reported.¹⁸ Hence,
415 changes in calf muscle power throughout a competitive season needs to be specifically explored to
416 confirm whether changes in calf muscle power take place over a season.

417

418 The eccentric-concentric power developed under load has been shown to be ~22% lower on average in
419 presence of an Achilles tendinopathy compared to the least symptomatic or uninjured leg.¹⁵ The mean
420 power recorded in the least symptomatic or uninjured leg (384 ± 160 W) in this latter study assessed
421 using a linear position transducer and a stranding weight machine under 33 kg load was considerably
422 lower than our lowest reported mean of 585 ± 179 W assessed at 35 kg using a dumbbell and the CR_{app}.
423 Although differences in methodology and equipment might have contributed to the 200 W power
424 difference between studies to a certain extent, the magnitude of the difference in weighted power
425 reflects the need for rugby union specific measures rather than reliance on general population outcomes.
426 Even though the two assessment methods differed and should not be considered interchangeable, it is
427 worth noting that both approaches demonstrated comparable test-retest reliability between days. Whilst
428 the relative reliability using the weight machine approach was marginally superior (ICC 0.76–0.86) to
429 ours (ICC 0.70–0.88), the absolute reliability was lower in the weight machine (CV 15–17%) compared
430 to our approach (7–14%).

431

432 Whilst forwards were more powerful than backs, backs completed approximately three more repetitions
433 and covered 30.2 cm more positive displacement than forwards during the concentric-eccentric
434 endurance test when considering rugby-related factors only. A number of studies have used the
435 concentric-eccentric endurance test, although variations in protocol exists¹³ that are likely to influence
436 outcomes. For the number of repetitions, normative outcomes reported include 24 repetitions across

437 males and females aged 20–81 years¹⁰ and 40 repetitions in uninjured young adults.²⁹ For the total
438 positive work, the average performance for the non-injured legs of individuals reported are typically
439 around 2000 J when based on heel displacement,^{15,31,36} which agrees with our outcomes, although mean
440 values of around 3000 J have also been documented.³⁰

441

442 The study with the most comparable calf raise endurance test method to ours (i.e., conducted on a step
443 rather than on an incline or from the floor) assessed individuals 2 years post Achilles tendon rupture.³⁶
444 Their mean outcomes (20 repetitions and 2000 J) on the uninjured legs are comparable to our findings
445 in rugby union players, which might be somewhat unexpected given the younger age of our cohort,
446 their greater body mass, and their relatively high physical activity levels. Rugby union is a physical
447 high-intensity sport¹ that emphasises strength, speed, and power abilities in testing and training.^{2,25} The
448 muscular endurance abilities of players remain largely undocumented in this sport. The current data
449 suggest that although rugby athletes may be more powerful than the general population, their calf
450 muscle endurance are comparable to the general population. Without targeted calf muscle endurance
451 training, male rugby athletes competing in Club to International level rugby on average should complete
452 20 calf raise repetitions and 2000 J of positive work when assessed on a step.

453

454 A history of muscle tendon unit injury and greater BMI negatively affected the number of repetitions
455 completed during endurance testing, with forwards and backs no longer exhibiting differences in this
456 metric. In other words, the greater frequency of muscle tendon unit injuries and greater BMI in forwards
457 than backs explained the lower number of repetitions detected in forwards. These results support prior
458 research findings that previous calf muscle tendon injuries^{30,36} and BMI¹⁰ can have negative impacts on
459 calf muscle endurance. Residual deficits may be important to continue addressing to prevent future calf
460 muscle and tendon injuries in previously injured rugby union athletes.⁵

461

462 The data from this study provide normative calf muscle function values for uninjured male rugby union
463 athletes in New Zealand, and can be used to inform medical teams, coaching staff, strength and
464 condition practitioners, and athletes. **Normative data are useful to determine the baseline distribution of**

465 an outcome measure and set a standard against which individual outcomes can be assessed.³⁷ Using the
466 normative equations, coaching staff can gain a better understanding as to whether individual athletes
467 should prioritise calf muscle training based on achieving or not anticipated outcomes. Given that
468 Achilles tendinopathies or ruptures affect performance on the power and endurance tests,^{15, 30} the
469 normative values may be useful to inform clinical management of athletes sustaining such injuries when
470 pre-injury outcome data are unavailable.

471

472 This study was limited to male rugby union athletes and the results should not be generalised to female
473 rugby union or sevens' athletes given their unique requirements.^{38, 39} Although the data have the
474 potential to inform the clinical management of injured players, our study involved uninjured players
475 only to establish benchmark values and normative reference values. Therefore, individuals with a
476 current Achilles tendon or calf muscle injury were excluded, and future research is needed to confirm
477 the usefulness of the proposed calf muscle testing battery to establish the extent of injuries, track
478 rehabilitation progress, and inform return to play decisions in rugby union. Finally, a set external load
479 of 35 kg was used for the weighted power test based on prior research,¹⁵ for ease of implementation,
480 and to set a common benchmark load. Future work is required to determine whether implementing a
481 relative load (e.g., percentage of body mass) would provide more meaningful outcomes than using an
482 absolute load for rugby union players and ascertain generalisation across ages, levels, genders, and
483 playing positions.

484

485 **Conclusions**

486 The results generated from the test battery and CR_{app} were reliable and valid, with test-retest improving
487 after a familiarisation session. Monitoring calf muscle function regularly can be used to track athletes
488 during rehabilitation and training to inform athlete management. Concurrent monitoring of injury
489 incidence could provide further understanding of injury risk factors and inform prevention strategies.
490 The intention of testing should be to identify deficits or asymmetry to ensure appropriate exercise
491 prescription for the need of the individual athlete.

492

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494 XXXX

495

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498

499 **CONFLICT OF INTEREST**

500 XXXX

501

502 **REFERENCES**

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628

Table 1. Demographic characteristics of rugby union players involved in establishing validity and reliability of outcomes by playing position.

Variable	Validity (<i>n</i> = 20)		Reliability (<i>n</i> = 18)	
	Forward (<i>n</i> = 13)	Back (<i>n</i> = 7)	Forward (<i>n</i> = 7)	Back (<i>n</i> = 11)
Age (years)	21.2 ± 1.7	20.0 ± 0.6	21.2 ± 1.7	21.6 ± 0.9
(min, max)	(18.9, 24.4)	(19.1, 21.1)	(18.9, 24.4)	(20.5, 22.9)
Height (m)	1.9 ± 0.1	1.8 ± 0.0	1.9 ± 0.1	1.9 ± 0.1
(min, max)	(1.8, 2.0)	(1.8, 1.9)	(1.8, 2.0)	(1.8, 2.0)
Mass (kg)	111.2 ± 13.3	89.8 ± 8.6	111.2 ± 13.3	105.7 ± 7.8
(min, max)	(94.0, 141.5)	(77.3, 100.2)	(94.0, 141.5)	(95.6, 113.6)
BMI (kg/m²)	32.1 ± 3.6	27.4 ± 2.6	32.1 ± 3.6	30.3 ± 3.3
(min, max)	(28.6, 38.4)	(24.5, 31.5)	(28.6, 38.4)	(26.8, 35.0)
Dominant (right:left)^a	11:2	6:1	11:2	6:1
MTU (no:yes)^b	10:3	3:4	10:3	6:1

Values are mean ± standard deviation, range (minimum, maximum), and ratios.

^a Leg used to kick a ball.

^b Self-reported previous calf muscle or Achilles tendon injury requiring medical care.

Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit.

Table 2. Demographic characteristics of 120 rugby union players involved in the normative dataset by playing level and position.

Variable	International (<i>n</i> = 29)		Super Rugby (<i>n</i> = 34)		Provincial (<i>n</i> = 36)		Club (<i>n</i> = 21)	
	Forward	Back	Forward	Back	Forward	Back	Forward	Back
	(<i>n</i> = 19)	(<i>n</i> = 10)	(<i>n</i> = 17)	(<i>n</i> = 17)	(<i>n</i> = 20)	(<i>n</i> = 16)	(<i>n</i> = 10)	(<i>n</i> = 11)
Age (years)	27.0 ± 3.3	26.4 ± 3.5	27.3 ± 4.7	24.4 ± 3.1	22.3 ± 2.1	24.2 ± 2.3	20.8 ± 1.4	19.9 ± 1.0
(min, max)	(20.8, 34.0)	(21.7, 32.0)	(20.0, 36.3)	(21.1, 30.4)	(19.6, 27.8)	(20.9, 29.3)	(18.8, 23.4)	(18.4, 21.9)
Height (m)	1.9 ± 0.1	1.8 ± 0.9	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.1	1.9 ± 0.1	1.8 ± 0.1
(min, max)	(1.8, 2.0)	(1.7, 2.0)	(1.8, 2.0)	(1.7, 1.9)	(1.8, 2.0)	(1.7, 2.0)	(1.7, 2.0)	(1.8, 2.0)
Mass (kg)	118.3 ± 8.5	93.1 ± 11.7	113.9 ± 7.7	94.8 ± 10.2	108.3 ± 8.8	91.1 ± 5.9	108.3 ± 7.3	88.3 ± 8.2
(min, max)	(104.5, 132.0)	(75.3, 110.5)	(103.0, 128.0)	(73.0, 112.0)	(93.0, 124.8)	(81.0, 105.6)	(93.5, 116.1)	(67.6, 99.9)
BMI (kg/m²)	32.5 ± 2.8	28.1 ± 2.1	31.4 ± 2.5	27.9 ± 1.7	30.5 ± 2.8	27.5 ± 1.4	30.9 ± 3.1	26.1 ± 2.1
(min, max)	(28.9, 38.6)	(25.5, 32.2)	(28.2, 35.7)	(24.9, 32.0)	(27.0, 36.6)	(24.6, 29.9)	(26.9, 38.0)	(22.1, 29.2)
Dominant (right:left)^a	18:1	9:1	14:3	15:2	18:2	14:2	6:4	10:1
MTU (no:yes)^b	19:18	17:5	24:12	34:1	34:4	30:3	20:1	22:1

Values are mean ± standard deviation, range (minimum, maximum), and ratios.

^a Leg used to kick a ball.

^b Self-reported previous calf muscle or Achilles tendon injury requiring medical care.

Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit.

Table 3. Comparison between Calf Raise application and laboratory measures from 20 participants.

Variable	App	Lab	Diff [†]	ICC	TE [†]	CV (%) [†]
Eccentric-concentric bodyweight						
Power app vs. force plate (W)	669.6 ± 121.4 (426.0, 965.0)	748.1 ± 140.1 (473.8, 1044.8)	78.6 ± 64.1 [58.1, 99.1]	0.89 [0.79, 0.94]	45.3 [37.1, 58.2]	6.4 [5.5, 6.6]
Power app vs. 3D mocap (W)	669.6 ± 121.4 (426.0, 965.0)	633.6 ± 107.3 (413.1, 886.2)	-35.9 ± 50.9 [-52.2, -19.7]	0.91 [0.83, 0.95]	36.0 [29.5, 46.2]	5.5 [4.5, 7.1]
Eccentric-concentric bodyweight + 35 kg						
Power app vs. force plate (W)	627.2 ± 96.6 (468.0, 839.0)	619.2 ± 103.3 (411.8, 869.9)	-7.9 ± 58.5 [-26.7, 10.8]	0.84 [0.71, 0.91]	41.4 [33.9, 53.1]	6.6 [5.4, 8.5]
Power app vs. 3D mocap (W)	627.2 ± 96.6 (468.0, 839.0)	602.8 ± 83.4 (454.9, 814.6)	-24.4 ± 40.7 [-37.4, -11.4]	0.90 [0.82, 0.95]	28.8 [23.6, 36.9]	4.7 [3.8, 6.0]
Concentric-eccentric endurance						
Repetitions (n)	17 ± 4 (9, 23)	17 ± 4 (9, 23)	0 ± 0 [0, 0]	1.00 [--]	0.0 [--]	0.0 [--]
Displacement (cm)	218.4 ± 46.8 (102.3, 309.8)	175.0 ± 36.4 (81.7, 238.3)	-43.4 ± 12.2 [-47.3, -39.4]	0.96 [0.93, 0.98]	8.6 [7.1, 11.1]	4.4 [3.6, 5.6]
Work app vs. force plate (J)	2202.1 ± 514.2 (1242.0, 3484.9)	1703.8 ± 399.1 (955.6, 2725.0)	-498.3 ± 132.0 [-540.5, -456.1]	0.96 [0.93, 0.98]	93.3 [76.4, 119.8]	4.8 [3.9, 6.1]

Work app vs. 3D mocap (J)	2202.1 ± 514.2	1764.8 ± 407.1	-437.3 ± 124.8	0.97	88.2	4.4
	(1242.0, 3484.9)	(991.4, 2801.4)	[-477.2, -397.3]	[0.94, 0.98]	[72.3, 113.3]	[3.6, 5.7]

Data are mean ± standard deviations, ranges (minimum, maximum), and statistical estimates with 95% confidence intervals [lower, upper].

† Calculated as laboratory measure minus Calf Raise application measure.

Abbreviations: BW, bodyweight. CV, coefficient of variation. Diff, difference. ICC, intraclass correlation coefficient. Mocap, motion capture. TE, typical error.

Table 4. Comparison between Calf Raise application measures between test-retest occasions from 18 participants.

Variable	D1	D2	D3	ICC	ICC	TE	TE	CV (%)	CV (%)
				D2 – D1	D3 – D2	D2 – D1	D3 – D2	D2 – D1	D3 – D2
Eccentric-concentric power									
Bodyweight (W)	688.5 ± 152.3	695.6 ± 115.6	684.2 ± 129.0	0.72	0.83	73.4	51.0	10.6	7.4
	(501.9, 1158.0)	(441.8, 1000.1)	(458.4, 1055.7)	[0.51, 0.84]	[0.70, 0.91]	[59.5, 95.7]	[41.2, 66.8]	[8.6, 13.8]	[6.0, 9.7]
Bodyweight + 35 kg (W)	715.8 ± 201.4	704.0 ± 152.6	697.1 ± 146.7	0.70	0.88	100.1	53.2	14.1	7.6
	(435.9, 1340.1)	(361.0, 1038.9)	(453.3, 1105.5)	[0.48, 0.83]	[0.78, 0.94]	[81.2, 131.6]	[43.1, 69.4]	[11.4, 18.4]	[6.2, 9.9]
Concentric-eccentric endurance									
Repetitions (n)	20 ± 5	21 ± 5	20 ± 5	0.75	0.88	2.8	1.8	13.3	8.9
	(11, 31)	(11, 34)	(11, 29)	[0.56, 0.86]	[0.78, 0.94]	[2.2, 3.6]	[1.5, 2.4]	[10.8, 17.3]	[7.2, 11.6]
Displacement (cm)	212.4 ± 53.2	223.7 ± 62.6	206.9 ± 54.8	0.72	0.88	31.3	20.9	14.4	9.7
	(125.0, 353.0)	(104.3, 359.7)	(123.2, 335.5)	[0.52, 0.85]	[0.78, 0.94]	[25.4, 40.9]	[16.9, 27.2]	[11.7, 18.7]	[7.9, 12.6]
Work (J)	2247.4 ± 571.7	2337.8 ± 619.8	2163.8 ± 566.1	0.67	0.87	345.7	219.8	15.1	9.8
	(1345.6, 3509.3)	(1276.7, 3872.2)	(1290.9, 3629.7)	[0.45, 0.82]	[0.76, 0.93]	[280.4, 451.0]	[178.3, 286.7]	[12.2, 19.7]	[7.9, 12.7]

Data are mean ± standard deviations, ranges (minimum, maximum), and statistical estimates with 95% confidence intervals [lower, upper].

Abbreviations: BW, bodyweight. CV, coefficient of variation. D1, day one. D2, day 2. D3, day 3. ICC, intraclass correlation coefficient. TE, typical error.

Table 5. Calf muscle test outcomes by position and playing level for dominant and non-dominant legs combined. Values are mean \pm standard deviation and range (minimum, maximum).

Variable	International (n = 29)		Super Rugby (n = 34)		Provincial (n = 36)		Club (n = 21)	
	Forward	Back	Forward	Back	Forward	Back	Forward	Back
	(n = 19)	(n = 10)	(n = 17)	(n = 17)	(n = 20)	(n = 16)	(n = 10)	(n = 11)
Eccentric-concentric power								
Bodyweight (W)	732.9 \pm 108.6	602.6 \pm 108.7	796.1 \pm 126.7	684.4 \pm 141.0	675.3 \pm 106.4	661.1 \pm 107.3	659.0 \pm 100.8	619.8 \pm 161.9
(min, max)	(519.0, 1007.0)	(395.0, 867.0)	(588.0, 1082.0)	(441.0, 1055.0)	(435.0, 901.0)	(442.0, 1030.0)	(485.0, 870.0)	(396.0, 929.0)
Bodyweight + 35 kg (W)	772.5 \pm 136.3	589.2 \pm 101.0	757.9 \pm 160.2	722.9 \pm 173.1	674.4 \pm 125.1	672.0 \pm 143.4	629.7 \pm 149.7	584.7 \pm 179.0
(min, max)	(502.0, 1098.0)	(375.0, 784.0)	(451.0, 1145.0)	(429.0, 1174.0)	(435.0, 942.0)	(361.0, 924.0)	(328.0, 909.0)	(334.0, 979.0)
Concentric-eccentric endurance								
Repetitions (n)	20 \pm 4	20 \pm 4	18 \pm 4	22 \pm 6	21 \pm 6	23 \pm 7	18 \pm 6	22 \pm 7
(min, max)	(12, 32)	(13, 29)	(12, 29)	(9, 32)	(11, 34)	(12, 46)	(7, 29)	(13, 37)
Displacement (cm)	188.9 \pm 46.0	185.8 \pm 35.8	178.8 \pm 39.7	208.7 \pm 56.1	177.3 \pm 43.1	228.1 \pm 60.6	185.8 \pm 43.5	212.8 \pm 66.7
(min, max)	(118.0, 317.0)	(135.0, 263.0)	(120.0, 287.0)	(115.0, 331.0)	(102.0, 313.0)	(104.0, 353.0)	(88.0, 287.0)	(121.0, 362.0)
Work (J)	2078.5 \pm 556.1	1952.1 \pm 511.7	1987.6 \pm 397.6	1979.1 \pm 566.8	1887.4 \pm 439.3	2043.9 \pm 550.7	1981.7 \pm 480.9	1803.2 \pm 444.6
(min, max)	(1154.0, 3302.0)	(1020.0, 2903.0)	(1357.0, 2958.0)	(1111.0, 3119.0)	(1170.0, 3122.0)	(889.0, 3360.0)	(936.0, 2822.0)	(1060.0, 2626.0)

Table 6. Summary of the generalised estimation equation analyses for all calf muscle test outcomes.

Variable	Estimate [lower, upper]	P-value
Bodyweight (W)		
Model A (rugby only)		
Intercept	714.3 [670.3, 758.4]	<0.001
Position		
Backs (Forwards)	-72.8 [-112.2, -33.3]	<0.001
Level		
Super (International)	58.8 [4.0, 113.6]	0.035
Provincial (International)	-8.7 [-63.5, 46.0]	0.755
Club (International)	-33.0 [-94.7, 28.8]	0.295
Provincial (Super)	-67.6 [-118.8, -16.3]	0.010
Club (Super)	-91.8 [-150.4, -33.3]	0.002
Club (Provincial)	-24.3 [-82.9, 34.3]	0.417
Model B (rugby plus others)		
<i>Idem to Model A</i>		
Bodyweight + 35 kg (W)		
Model A (rugby only)		
Intercept	718.6 [663.1, 774.1]	<0.001
Position		
Backs (Forwards)	-59.3 [-108.1, -10.5]	0.017
Level		
Super (International)	49.0 [-19.2, 117.2]	0.159
Provincial (International)	-15.1 [-83.2, 53.1]	0.665
Club (International)	-77.2 [-153.9, -0.5]	0.049
Provincial (Super)	-64.1 [-127.3, -0.9]	0.047
Club (Super)	-126.2 [-198.4, -54.0]	0.001
Club (Provincial)	-62.2 [-134.4, 10.1]	0.092
Model B (rugby plus others)		
Intercept	291.8 [24.9, 558.7]	0.032
Level		
Super (International)	52.3 [-15.1, 119.7]	0.128

Provincial (International)	-4.2 [-72.0, 63.5]	0.903
Club (International)	-57.9 [-135.1, 19.4]	0.142
Provincial (Super)	-56.5 [-118.9, 5.9]	0.076
Club (Super)	-110.1 [-182.3, -38.0]	0.003
Club (Provincial)	-53.6 [-125.3, 18.0]	0.142
BMI	13.3 [4.6, 22.0]	0.003
Concentric-eccentric endurance		
Repetitions (n)		
Model A (rugby only)		
Intercept	19.4 [18.4, 20.4]	<0.001
Position		
Backs (Forwards)	2.7 [1.2, 4.3]	0.001
Model B (rugby plus others)		
Intercept	33.1 [25.7, 40.4]	<0.001
MTU		
Yes	-1.4 [-2.4, -0.3]	0.011
BMI	-0.4 [-0.7, -0.2]	0.001
Displacement (cm)		
Model A (rugby only)		
Intercept	199.9 [187.7, 212.1]	<0.001
Position		
Backs (Forwards)	30.2 [12.3, 48.2]	0.001
Model B (rugby plus others)		
Intercept	286.5 [203.5, 321.8]	<0.001
Position		
Backs (Forwards)	27.9 [10.1, 45.8]	0.002
Age	-2.5 [-4.9, -0.2]	0.034
Work (J)		
Intercept	1977.4 [1895.8, 2058.9]	<0.001

Estimates are presented with their 95% CI [lower, upper]^{†‡}.

[†] Estimates derive from generalized estimation equation models with forwards and International as reference conditions.

Pairwise comparisons derive from marginal linear predictions.

[‡] Comparisons are presented as: Comparison (reference). For example, Backs (Forwards) indicate that backs are compared against forwards.

Abbreviations: BMI, body mass index. MTU, triceps surae muscle-tendon unit.

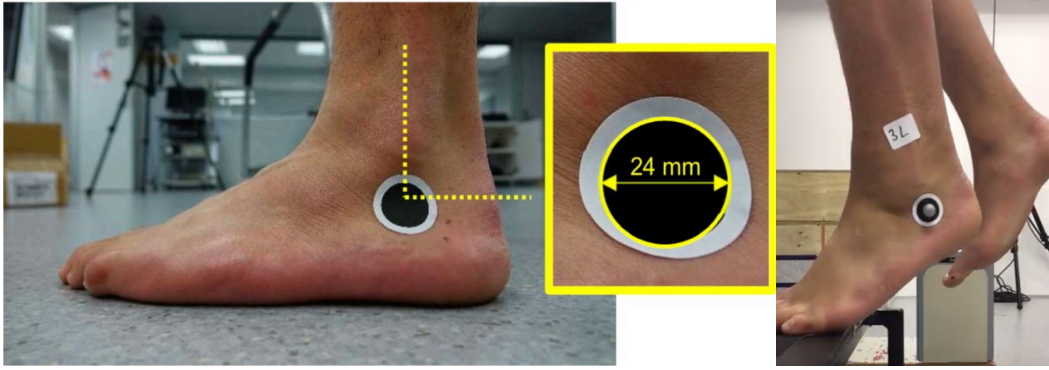


Figure 1.

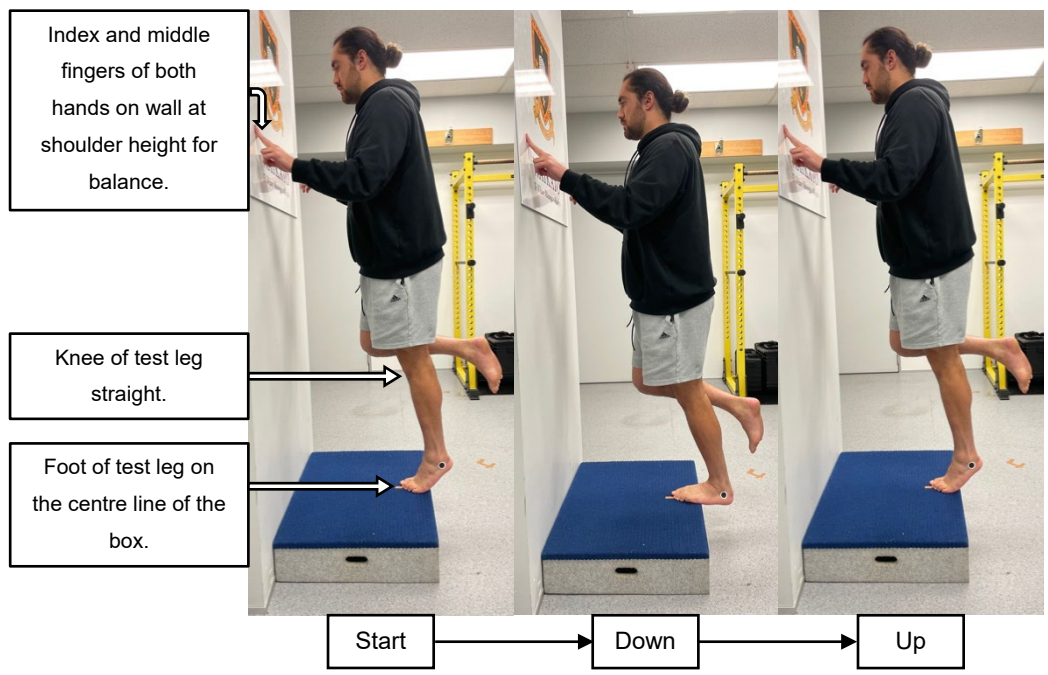


Figure 2.

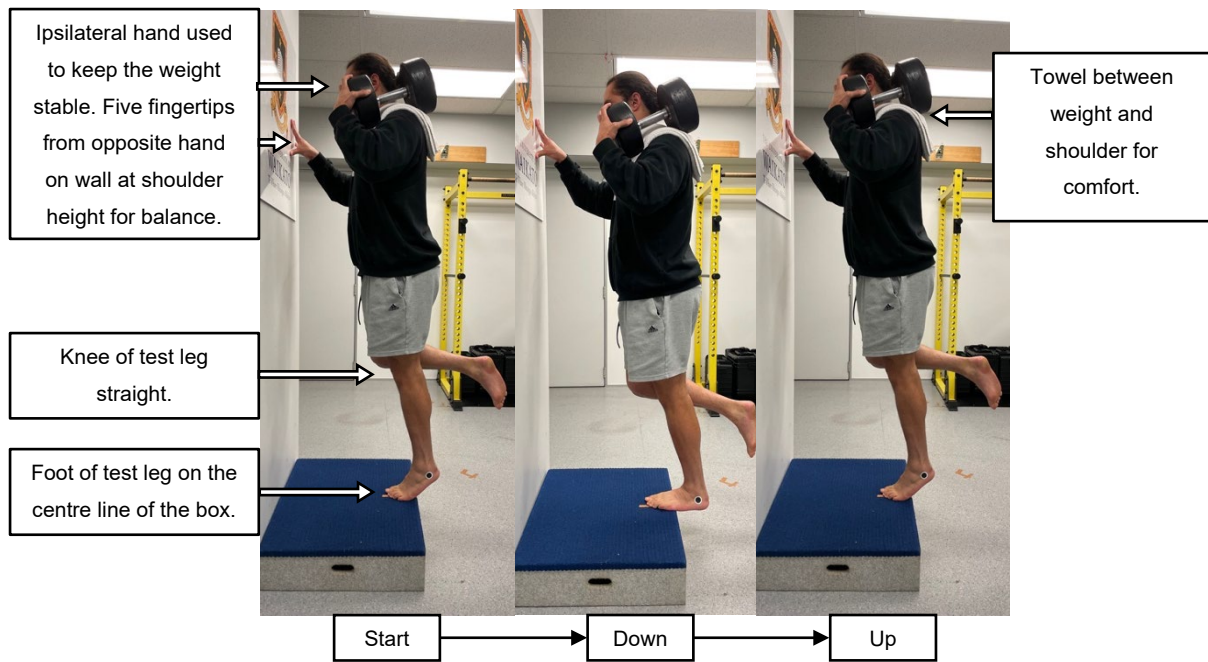


Figure 3.

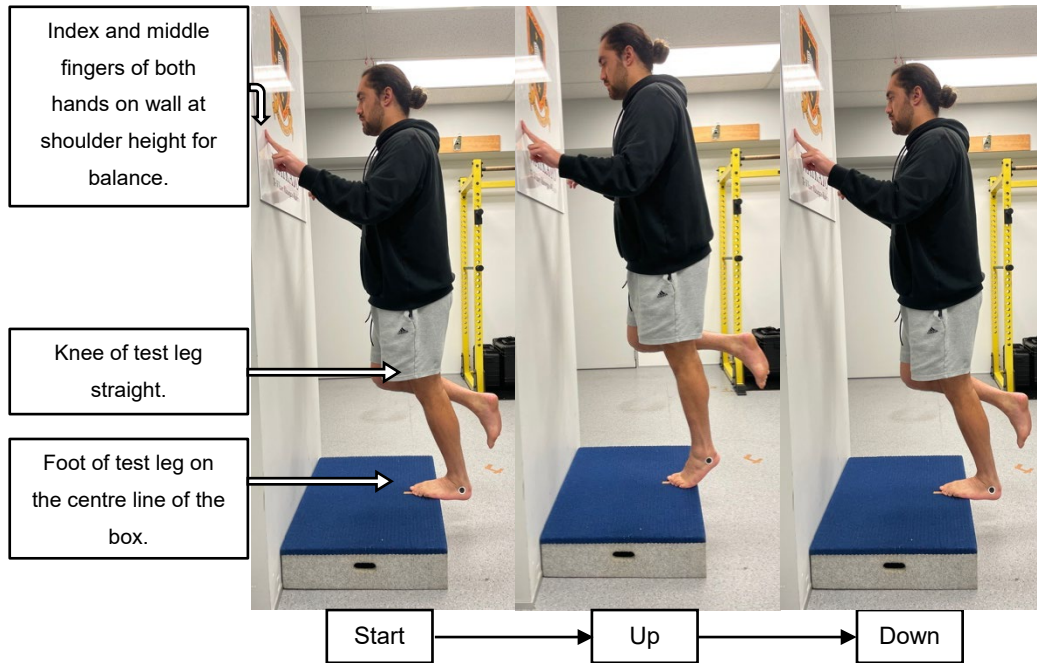


Figure 4.

FIGURE CAPTIONS

Figure 1. Calf muscle test marker placement (beneath the malleolus, in-line with the calcaneus) with and without reflective marker.

Figure 2. Eccentric-concentric bodyweight power test. Start, Down, Up = One repetition. Test involves completing three repetitions.

Figure 3. Eccentric-concentric weighted power test. Start, Down, Up = One repetition. Test involves completing three repetitions.

Figure 4. Concentric-eccentric endurance test. Start, Up, Down = One repetition. Test involves completing as many repetitions as possible.