

Article

The effects of conventional and oval chainrings on patellofemoral loading during road cycling: an exploration using musculoskeletal simulation

Sinclair, Jonathan Kenneth, Stainton, Philip and Sant, Benjamin

Available at <http://clock.uclan.ac.uk/21138/>

Sinclair, Jonathan Kenneth ORCID: 0000-0002-2231-3732, Stainton, Philip and Sant, Benjamin (2017) The effects of conventional and oval chainrings on patellofemoral loading during road cycling: an exploration using musculoskeletal simulation. Sport Sciences for Health . ISSN 1824-7490

It is advisable to refer to the publisher's version if you intend to cite from the work.

<http://dx.doi.org/10.1007/s11332-017-0401-6>

For more information about UCLan's research in this area go to <http://www.uclan.ac.uk/researchgroups/> and search for <name of research Group>.

For information about Research generally at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLoK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the [policies](#) page.

1 **The effects of conventional and oval chainrings on patellofemoral loading during road**
2 **cycling: an exploration using musculoskeletal simulation.**

3 *Jonathan Sinclair¹, Philip Stainton¹, & Benjamin Sant¹*

4 1. *Centre for Applied Sport & Exercise Sciences, Faculty of Health & Wellbeing,*
5 *University of Central Lancashire, Lancashire, UK.*

6
7 **Contact Details:**

8 Dr. Jonathan Sinclair

9 Centre for Applied Sport & Exercise Sciences

10 Faculty of Health & Wellbeing

11 Preston

12 Lancashire

13 PR1 2HE

14 e-mail: jksinclair@uclan.ac.uk

15 **Keywords:** Biomechanics; cycling, chainring, patellofemoral, pathology

16 **Abstract**

17 *PURPOSE:* The aim of the current investigation was to utilize a musculoskeletal simulation
18 approach to resolve muscle forces during the pedal cycle, in order to specifically examine the
19 effects of chainring geometry on patellofemoral loading during cycling.

20 *METHODS:* Fifteen healthy male recreational cyclists rode a stationary cycle ergometer at a
21 fixed cadence of 70 RPM in two chainring conditions (round and oval). Patellofemoral
22 loading was explored using a musculoskeletal simulation and mathematical modelling
23 approach. Differences between chainring conditions across the entire pedal cycle were
24 examined using 1-dimensional statistical parametric mapping and patellofemoral force
25 experienced per 20 km was explored using a paired samples t-test.

26 *RESULTS*: No significant ($P>0.05$) differences in patellofemoral force or stress were found
27 throughout the pedal cycle between chainring conditions. It was also shown that no
28 significant ($P>0.05$) differences in patellofemoral force per 20 km joint were evident (round
29 $38576.40 \text{ N/kg}\cdot\text{s}$ & oval = $35637.00 \text{ N/kg}\cdot\text{s}$).

30 *CONCLUSIONS*: The current analysis found no effects of chainring geometry, on the forces
31 experienced by the patellofemoral joint during the pedal cycle.

32

33 **Introduction**

34 During linear road cycling using traditional circular chainrings, the application of tangential
35 force is lowest when the crank is vertically aligned, either at 0 or 180° of the pedal cycle,
36 and maximal when the crank is horizontally aligned (1). The points during the pedal cycle
37 where tangential force is lowest are typically referred to as upper and lower dead points (2).
38 In an attempt to improve road cycling performance and maximize the application of effective
39 force during the pedal cycle, oval chainrings were introduced, whereby the axes of the
40 chainring are not perpendicular (3). This shape means that the moment arm of the force being
41 applied to the chain is reduced at the dead points of the pedal cycle but increased when the
42 crank is horizontally aligned (3). This optimizes the period of the pedal cycle in which
43 tangential force is produced, and correspondingly reduces the time spent in the upper and
44 lower dead points (4).

45

46 Quantitative analyses investigating performance parameters with oval chainrings have shown
47 inconsistent findings. Hintzy et al., (4) showed that peak power output was significantly
48 higher when using a non-circular chainrings during short duration maximal spring cycling.
49 Hintzy & Horvais, (5) similarly found that higher maximal aerobic power was attained when
50 using a non-circular chainring during maximal incremental tests. Horvais et al., (6) examined

51 mechanical and physiological parameters during 8 minute submaximal and 8 s maximal tests.
52 During the submaximal test the oval chainring produced lower crank torques at 0° and 180°
53 and greater torques at 90° of the pedal cycle. During the sprint test, the biceps femoris
54 exhibited a longer burst of activation in the oval chainring condition. Conversely, Cordova et
55 al., (2) showed that there were no significant differences in physiological responses during an
56 incremental test until exhaustion. Similarly, Peiffer & Abbiss, (7) found that there were no
57 differences in physiological and performance parameters between oval and round chainrings
58 during a 10 km cycling time trial. Finally, Dagnese et al., (8) similarly showed that there were
59 no significant differences in lower extremity muscle activation magnitude between oval and
60 round chainrings.

61

62 Further to this, Bisi et al., (9) showed that oval chainrings altered lower extremity joint
63 kinetics, with reductions of 6% in the knee joint moment, which they identified may have
64 implications for chronic injury prevention at this joint. Importantly the knee joint is the
65 musculoskeletal structure most susceptible to chronic pathology in cyclists (10). Specifically,
66 patellofemoral pain is the most frequently experienced condition, affecting 36% of all regular
67 cyclists' and accounting for more than 57% of all time-loss injuries (11). Despite the
68 incidence of patellofemoral pain in cyclists it has received a paucity of attention in scientific
69 literature in relation to other athletic disciplines. Therefore, further exploration of this
70 condition is clearly warranted in cycling specific analyses.

71

72 Patellofemoral pain is initiated by activities that place frequent and excessive mechanical
73 loads at the joint (12, 13). Therefore, quantification of patellofemoral loading is important in
74 cycling specific activities as we seek to understand more about this condition and the
75 potential mechanisms that may be important to prevent the high incidence of patellofemoral

76 pain. Although validated mathematical models of the patellofemoral joint are available in
77 biomechanical literature (14, 15), they typically require inverse joint dynamics to resolve
78 muscle kinetics as input parameters into the musculoskeletal algorithm. Whilst this is suitable
79 for movements which involve full foot contact with a force platform, this is not available for
80 cycling specific analyses, which may help to explain the lack of scientific attention
81 concerning to patellofemoral pain in road cycling.

82

83 However, advances in musculoskeletal modelling have led to the development of bespoke
84 software which allows skeletal muscle force distributions to be simulated during movement
85 using motion capture based data (16). To date, such approaches have not yet been utilized in
86 cycling specific analyses. The aim of the current investigation was therefore to utilize a
87 musculoskeletal simulation approach to resolve muscle forces during cycling to examine the
88 effects of chainring geometry on patellofemoral loading during the pedal cycle. A study of
89 this nature may provide important clinical information regarding the effects of different
90 chainring technology on the susceptibility of road cyclists to patellofemoral pain.

91

92 **Materials & methods**

93 *Participants*

94 Fifteen male recreational cyclists, who habitually utilized round chainrings for their training
95 volunteered to take part in this study. Cyclists were required to have at least 2 years of road
96 cycling experience and be free from musculoskeletal pathology at the time of data collection.

97 The mean characteristics of the participants were; age 28.11 ± 5.11 years, height 1.80 ± 0.10
98 m and body mass 75.10 ± 8.22 kg. The procedure utilized for this investigation was approved
99 by the University of Central Lancashire, Science, Technology, Engineering and Mathematics,
100 ethical committee (Ref: 511) and all participants provided written informed consent

101

102 *Procedure*

103 Participants rode a stationary cycle ergometer SRM 'Indoor Trainer' (SRM, Schoberer,
104 Germany) for 10 minutes at a fixed cadence of 70 RPM using a 52x15 gear ratio. To ensure
105 that the current investigation examined only the effects of the different chainrings, the set-up
106 parameters were constructed in accordance with previous recommendations (17), and
107 standardized between the two conditions. Cycling shoes (Northwave Sonic 2 Plus Road
108 Shoes, Northwave, Italy), pedals (Look Keo Classic 2, Look, Cedex, France) and cleats
109 (Look Keo Grip, 4.5° float, Look, Cedex, France) were consistent across all trials, and
110 adjusted so that the 1st metatarsal head was positioned superior to the pedal spindle (18). The
111 participants were provided with continuous visual feedback regarding their cadence, which
112 was visible via the SRM head unit (Powercontrol V, SRM, Schoberer, Germany).

113

114 The participants rode in two conditions one with a traditional round chainring (SRM power,
115 SRM, Schoberer, Germany) and one using an oval shaped chainring (Osymetric, standard,
116 USA), with a crank length of 172.5mm. To prevent any order effects in the experimental
117 data, the order in which participants rode in each chainring condition was counterbalanced
118 and a standardized rest period of 10 minutes was allowed between trials. The ergometer setup
119 was organized based on each participant own preference and maintained between the two
120 chainring conditions.

121

122 Kinematic information from the lower extremity joints was obtained using an eight camera
123 motion capture system (Qualisys Medical AB, Goteburg, Sweden) using a capture frequency
124 of 250 Hz. To define the anatomical frames of the thorax, pelvis, thighs, shanks and feet
125 retroreflective markers were placed at the C7, T12 and xiphoid process landmarks and also

126 positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine
127 (ASIS), posterior superior iliac spine (PSIS), medial and lateral malleoli, medial and lateral
128 femoral epicondyles, greater trochanter, calcaneus, first metatarsal and fifth metatarsal.
129 Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were
130 positioned onto the thigh and shank segments. In addition to these the foot segments were
131 tracked via the calcaneus, first metatarsal and fifth metatarsal, the pelvic segment was tracked
132 using the PSIS and ASIS markers and the thorax segment was tracked using the T12, C7 and
133 xiphoid markers. Static calibration trials were obtained with the participant in the anatomical
134 position in order for the positions of the anatomical markers to be referenced in relation to the
135 tracking clusters/markers. A static trial was conducted with the participant in the anatomical
136 position in order for the anatomical positions to be referenced in relation to the tracking
137 markers, following which those not required for dynamic data were removed.

138

139 *Processing*

140 Dynamic trials were digitized using Qualisys Track Manager in order to identify anatomical
141 and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD,
142 USA). Marker data were smoothed using a cut-off frequency 12 Hz using a low-pass
143 Butterworth 4th order zero-lag filter; this was established using residual analysis similar to
144 Sinclair et al., (19).

145

146 Data from five pedal cycles in each chainring condition were exported from Visual 3D into
147 OpenSim 3.3 software (Simtk.org). The five extracted pedal cycles were obtained during
148 minutes 4-6 of the experimental protocol, and the pedal cycle itself was delineated in
149 accordance with Sinclair et al., (19). A validated musculoskeletal model (gait2392) with 8
150 segments, 19 degrees of freedom and 92 musculotendon actuators (Delp et al., 2007) was

151 used to resolve muscle kinetics during the pedal cycle. The model was scaled for each
152 participant using the anthropometrics and segment inertial properties generated from the
153 static trial to account for the dimensions of each athlete. We firstly performed a residual
154 reduction algorithm (RRA) within OpenSim, this utilizes the inverse kinematics that were
155 exported from Visual 3D. The RRA calculates the joint torques required to re-create the
156 dynamic motion. The RRA calculations produced root mean squared errors $<2^\circ$, which
157 correspond with the recommendations for good quality data. Following the RRA, the
158 computed muscle control (CMC) procedure was then employed to estimate a set of muscle
159 force patterns allowing the model to replicate the required kinematics (20). The CMC
160 procedure works by estimating the required muscle forces to produce the net joint torques.

161

162 Patellofemoral loading during cycling was quantified using a model adapted from van Eijden
163 et al., (14) in accordance with the protocol of Willson et al., (21). A key drawback of this
164 model is that co-contraction of the knee flexor musculature is not accounted for. Taking this
165 into account, summed hamstring and gastrocnemius forces derived from the CMC procedure
166 were multiplied by their estimated knee joint muscle moment arms as a function of knee
167 flexion angle (22) and then added together to determine the knee flexor torque during the
168 pedal cycle. In addition to this the knee extensor torque was also calculated by dividing the
169 summed quadriceps forces by this muscle groups' knee joint muscle moment arms as a
170 function of knee flexion angle (14). The knee flexor and extensor torques were then summed
171 and subsequently divided by the quadriceps muscle moment arm (14) to obtain quadriceps
172 force adjusted for co-contraction of the knee flexor muscles (21). Patellofemoral force was
173 quantified by multiplying the derived quadriceps force by a constant which was obtained by
174 using the data of Eijden et al., (14). Finally, patellofemoral joint stress was quantified by
175 dividing the patellofemoral force by the patellofemoral contact area. Patellofemoral contact

176 areas were obtained by fitting a polynomial curve to the sex specific data of Besier et al.,
177 (12), who estimated patellofemoral contact areas as a function of the knee flexion angle using
178 MRI.

179

180 Following this the patellofemoral force, muscle force and knee flexion angle data for each
181 participant during the entire pedal cycle were extracted and time normalized to 101 data
182 points. All joint and muscle force parameters were subsequently normalized by dividing the
183 net values by body mass (N/kg). In addition to this, the patellofemoral force integral during
184 the pedal cycle was obtained using a trapezoidal function. As cycling requires a uniquely
185 recurrent movement pattern, with a significant number of pedal cycles to complete typical
186 training/ competitive distances, the total patellofemoral force experienced per 20 km was also
187 extracted. This was resolved firstly by quantifying the velocity of the bicycle using the gear
188 ratio, cadence and typical wheel diameter/ tire width. Using this information (neglecting for
189 air resistance and assuming that the velocity was uniform) the time taken to cycle 20 km
190 could then be calculated. From this the number of pedal cycles required to complete the
191 aforementioned distance was calculated. Finally, in accordance with Sinclair et al., (23) the
192 patellofemoral force integral was multiplied by the number of pedal cycles necessary to cycle
193 20 km to extract the patellofemoral force experienced during this distance.

194

195 *Analyses*

196 Differences in patellofemoral and muscle forces across the entire pedal cycle were examined
197 using 1-dimensional statistical parametric mapping with MATLAB 2017a (MATLAB,
198 MathWorks, Natick, USA), in accordance with (24), using the source code available at
199 <http://www.spm1d.org/>. For patellofemoral force per 20 km, descriptive statistics of means,
200 standard deviations (SD) and 95 % confidence intervals (95% CI) were calculated for both

201 chainring conditions. Differences in patellofemoral force per 20 km between chainring
202 conditions were examined using a paired samples t-test. Effect sizes were calculated using
203 partial eta² (η^2). The alpha (α) level for statistical significance was set at the 0.05 level
204 throughout. Discrete statistical tests were conducted using SPSS v23.0 (SPSS, USA).

205

206 **Results**

207 Table 1 and figures 1-6 present differences in muscle kinetics and patellofemoral loading as a
208 function of the different chainring conditions.

209

210 *Patellofemoral loading*

211 No significant differences ($P>0.05$) in patellofemoral loading were evident across the pedal
212 cycle as a function of the different chainring conditions (Figure 1-2). In addition, no
213 significant ($P>0.05$) differences in patellofemoral force per 20 km were evident between
214 chainring conditions (Table 1).

215

216 **@@@ TABLE 1 NEAR HERE @@@**

217 **@@@ FIGURE 1 NEAR HERE @@@**

218 **@@@ FIGURE 2 NEAR HERE @@@**

219

220 *Muscle kinetics*

221 No significant differences ($P>0.05$) in muscle kinetics were evident across the pedal cycle as
222 a function of the different chainring conditions (Figure 3-6).

223

224 **@@@ FIGURE 3 NEAR HERE @@@**

225 **@@@ FIGURE 4 NEAR HERE @@@**

226 @@@ **FIGURE 5 NEAR HERE** @@@

227 @@@ **FIGURE 6 NEAR HERE** @@@

228

229 **Discussion**

230 The aim of the current investigation was to examine the effects of chainring geometry on
231 patellofemoral loading throughout the pedal cycle using a statistical parametric mapping
232 approach. To the authors knowledge this represents the first investigation to quantify the
233 effects of different chainrings on the loads experienced by this joint throughout the pedal
234 cycle. Given the high incidence of patellofemoral pain in road cyclists this investigation may
235 provide important information concerning the effects of different bicycle technology
236 regarding cyclists' susceptibility to chronic pathologies.

237

238 The key observation from the current study is that no significant differences in patellofemoral
239 loading parameters were observed at any point during the pedal cycle as a function of the
240 different chainring geometries examined as a part of this investigation. This opposes the
241 proposition initiated by Bisi et al., (9) which denoted that the reduction in knee joint moment
242 observed in the oval chainring condition may have implications for chronic injury prevention
243 at this joint. This disagreement is likely due to the distinction between joint inverse dynamics
244 and specific indices of joint loading; it has been shown that alterations in joint torque do not
245 necessarily reflect changes in joint loading (25). Therefore, it can be concluded from this
246 investigation that chainring geometry does not appear to influence patellofemoral loading
247 during the pedal cycle.

248

249 It is proposed that this finding relates to the lack of statistical differences in muscle kinetics
250 between the two conditions. No differences in knee flexor/ extensor muscle kinetics were

251 observed between round and oval chainrings at any point during the pedal cycle. Importantly,
252 Herzog et al., (26) have shown that muscles are the main determinant of joint forces. In
253 addition, the current study showed that there were no differences in knee joint kinematics
254 throughout the pedal cycle, between the two chainring conditions. Taking into account that
255 patellofemoral contact area (12) and knee flexor/ extensor muscle moment arms (14, 22),
256 were modelled as a function of the knee joint angle, provides further insight into the absence
257 of statistical differences in patellofemoral loading between conditions.

258

259 There is a clear link between excessive patellofemoral joint kinetics and the aetiology and
260 progression of patellofemoral pain (12, 13). The current study represents the first
261 investigation firstly to explore patellofemoral kinetics during the pedal cycle using a
262 mathematical model that accounts for co-contraction of the knee flexor musculature but also
263 to quantify the loads experienced by this joint during a typical cycling training/ competitive
264 distance. The findings show that cyclists experience considerable patellofemoral loads,
265 indeed although the peak forces during the pedal cycle (round = 27.86 & oval = 25.92 N/kg)
266 are lower than those during the stance phase of running which range between; 31.29 - 76.4
267 N/kg (27-29); the cumulative loads observed during the current study (round = 38576.40
268 N/kg·s & oval = 35637.00 N/kg·s) over the same linear distance are larger than those
269 experienced during running which range between; 27774.07 - 30721.33 N/kg·s (23). This is a
270 thought-provoking statistic which helps to contextualize the high incidence of patellofemoral
271 pain in cyclists and highlights the lack of scientific research into the patellofemoral joint in
272 cycling. There is currently a clear requirement for both prophylactic and treatment
273 intervention studies in cycling which are almost entirely absent in scientific literature. This
274 will serve to address the underlying epidemiological factors associated with patellofemoral

275 pain in cyclists and most importantly initiate a body of clinical research concerning sustained
276 conservative treatment modalities.

277

278 **Limitations & conclusions**

279 A limitation of the current investigation is that only healthy cyclists were examined. It is
280 currently unknown whether cyclists with patellofemoral pain differ in their joint loading in
281 comparison to healthy athletes, but Dieter et al., (10) demonstrated that cyclists with
282 patellofemoral pain exhibit altered muscle activation patterns compared to healthy controls.
283 Therefore generalizations of the current observations results to cyclists with existing
284 patellofemoral symptoms should be made with caution. A second potential drawback is that
285 patellofemoral loading was extracted using a mathematical modelling approach. Whilst this
286 procedure was considered an improvement over previous approaches in that co-contraction of
287 the knee flexor musculature was accounted for; individualized muscle moment arms and
288 patellofemoral contact areas are still not available within biomechanical literature. Finally,
289 that the current investigation examined cyclists who do not habitually ride using oval shaped
290 chainrings, may limit the generalizability of the results, which may have differed had the
291 riders been more familiar with this chainring condition. Therefore, it is important for the
292 current investigation to be repeated using cyclists who habitually utilize oval chainrings,
293 which will allow more definitive conclusions to be drawn.

294

295 In conclusion, although the effects of altering the geometry of the chainring have been
296 investigated previously, current knowledge regarding the effects of oval chainrings on
297 patellofemoral loading during cycling is lacking. This study consequently adds to the current
298 literature base in the field of biomechanics by presenting a comprehensive examination of
299 patellofemoral loading parameters during linear cycling with both round and oval chainrings.

300 The findings from current work show that the no differences in patellofemoral loading were
301 evident between the two chainring conditions. This therefore indicates that chainring
302 geometry does not significantly influence patellofemoral loading linked to the aetiology of
303 patellofemoral pain during cycling.

304

305 **Acknowledgements**

306 We thank Gareth Shadwell for his technical assistance.

307

308 We thank Todd Pataky, Mark Robinson and Jos Vanrenterghem for their website
309 (<http://www.spm1d.org/>) and for generously providing the source code for this experiment.

310

311 **Compliance with ethical standards**

312 *Conflict of interest*

313 We declare that we have no conflict of interest.

314 *Ethical approval*

315 All procedures performed in studies involving human participants were in accordance with
316 the ethical standards of the institutional and the declaration of Helsinki.

317 *Informed consent*

318 All of the subjects provided written consent.

319

320 **References**

- 321 1. Ericson MO, Nisell R (1988). Efficiency of pedal forces during ergometer cycling. Int
322 J Sports Med 9: 118–122. DOI:10.1055/s-2007-1024991

- 323 2. Cordova A, Latasa I, Seco J, Villa G, Rodriguez-Falces J (2014). Physiological
324 responses during cycling with oval chainrings (Q-Ring) and circular chainrings. *J*
325 *Sports Sci Med* 13: 410-416.
- 326 3. Strutzenberger G, Wunsch T, Kroell J, Dastl J, Schwameder H (2014). Effect of
327 chainring ovality on joint power during cycling at different workloads and cadences.
328 *Sports Biomech* 13: 97-108. <http://dx.doi.org/10.1080/14763141.2014.908946>
- 329 4. Hintzy F, Grappe F, Belli A (2016). Effects of a Non-Circular Chainring on Sprint
330 Performance During a Cycle Ergometer Test. *J Sports Sci Med* 15: 223-228.
- 331 5. Hintzy F, Horvais N (2016). Non-circular chainring improves aerobic cycling
332 performance in non-cyclists. *Eur J Sport Sci* 16: 427-432.
333 <http://dx.doi.org/10.1080/17461391.2015.1086817>
- 334 6. Horvais N, Samozino P, Zameziati K, Hautier C, Hintzy F (2007). Effects of a non-
335 circular chainring on muscular, mechanical and physiological parameters during cycle
336 ergometer tests. *Isokinet Exerc Sci* 15: 271-279.
- 337 7. Peiffer JJ, Abbiss CR (2010). The influence of elliptical chainrings on 10 km cycling
338 time trial performance. *Int J Sports Physiol Perform* 5: 459-468.
339 <https://doi.org/10.1123/ijsp.5.4.459>
- 340 8. Dagnese F, Carpes FP, Martins ED, Stefanyshyn D, Mota CB (2011). Effects of a
341 noncircular chainring system on muscle activation during cycling. *J Electromyogr*
342 *Kinesiol* 21: 13–17. DOI: 10.1016/j.jelekin.2010.02.005
- 343 9. Bisi MC, Stagni R, Gnudi G, Cappello A (2010). Non-circular chain ring allows a
344 reduction of joint loading in cycling. *J Mech Med Biol* 10: 113–122. DOI:
345 <http://dx.doi.org/10.1142/S0219519410003228>

- 346 10. Dieter BP, McGowan CP, Stoll SK, Vella CA (2014). Muscle activation patterns and
347 patellofemoral pain in cyclists. *Med Sci Sports Exerc* 46: 753-761. DOI:
348 10.1249/MSS.0000000000000153
- 349 11. Clarsen B, Krosshaug T, Bahr R (2010). Overuse injuries in professional road
350 cyclists. *Am J Sports Med* 38: 2494–2501. DOI: 10.1177/0363546510376816
- 351 12. Besier TF, Draper CE, Gold GE, Beaupre GS, Delp SL. Patellofemoral joint contact
352 area increases with knee flexion and weight-bearing. *J Orthop Res* 2005; 23: 345–350.
353 DOI: 10.1016/j.orthres.2004.08.003
- 354 13. Ho KY, Blanchette MG, Powers CM (2012). The influence of heel height on
355 patellofemoral joint kinetics during walking. *Gait Posture* 36: 271-275. DOI:
356 10.1016/j.gaitpost.2012.03.008
- 357 14. van Eijden TM, Kouwenhoven E, Verburg J, Weijs WA (1986). A mathematical
358 model of the patellofemoral joint. *J Biomech* 19: 219–229.
359 [https://doi.org/10.1016/0021-9290\(86\)90154-5](https://doi.org/10.1016/0021-9290(86)90154-5)
- 360 15. Elias JJ, Wilson DR, Adamson R, Cosgarea AJ (2004). Evaluation of a computational
361 model used to predict the patellofemoral contact pressure distribution. *J Biomech* 37:
362 295-302. [https://doi.org/10.1016/S0021-9290\(03\)00306-3](https://doi.org/10.1016/S0021-9290(03)00306-3)
- 363 16. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, Thelen DG (2007).
364 OpenSim: open-source software to create and analyze dynamic simulations of
365 movement. *IEEE Trans Biomed Eng* 54: 1940-1950. DOI:
366 10.1109/TBME.2007.901024
- 367 17. de Vey Mestdagh, K. (1998). Personal perspective in search of an optimum cycling
368 posture. *Appl Ergon* 29: 325–334. DOI:10.1016/S0003-6870(97)00080-X

- 369 18. Menard, M., Domalain, M., Decatoire, A., & Lacouture, P. (2016). Influence of
370 saddle setback on pedalling technique effectiveness in cycling. *Sport Biomech* 15:
371 462-472. DOI: <http://dx.doi.org/10.1080/14763141.2016.1176244>
- 372 19. Sinclair J, Hebron J, Atkins S, Hurst H, Taylor PJ. (2014). The influence of 3D
373 kinematic and electromyographical parameters on cycling economy. *Acta Bioeng*
374 *Biomech* 16: 91-97. DOI: 10.5277/ABB-00049-2014-02
- 375 20. Thelen DG, Anderson FC, Delp SL (2003). Generating dynamic simulations of
376 movement using computed muscle control. *J Biomech* 36: 321–328.
377 DOI:10.1016/S0021-9290(02)00432-3
- 378 21. Willson JD, Ratcliff OM, Meardon SA, Willy RW (2015). Influence of step length
379 and landing pattern on patellofemoral joint kinetics during running. *Scand J Med Sci*
380 *Sports* 25: 736-743. DOI: 10.1111/sms.12383
- 381 22. Spoor CW, van Leeuwen JL (1992). Knee muscle moment arms from MRI and from
382 tendon travel. *J Biomech* 25: 201–206. [https://doi.org/10.1016/0021-9290\(92\)90276-7](https://doi.org/10.1016/0021-9290(92)90276-7)
- 383 23. Sinclair J, Richards J, Selfe J, Fau-Goodwin J, Shore H. (2016). The influence of
384 minimalist and maximalist footwear on patellofemoral kinetics during running. *J App*
385 *Biomech* 32: 359-364. DOI:10.1123/jab.2015-0249
- 386 24. Pataky TC, Robinson MA, Vanrenterghem J (2016). Region-of-interest analyses of
387 one-dimensional biomechanical trajectories: bridging 0D and 1D theory, augmenting
388 statistical power. *Peer J* 4: 2652-2664. DOI: 10.7717/peerj.2652
- 389 25. Kutzner I, Trepczynski A, Heller MO, Bergmann G (2013). Knee adduction moment
390 and medial contact force—facts about their correlation during gait. *PLoS One* 8:
391 e81036. <https://doi.org/10.1371/journal.pone.0081036>

- 392 26. Herzog W, Longino D, Clark A (2003). The role of muscles in joint adaptation and
393 degeneration. *Langenbecks Arch Surg* 388: 305-315. DOI:10.1007/s00423-003-0402-
394 6
- 395 27. Kulmala JP, Avela J, Pasanen K, Parkkari J (2013). Forefoot strikers exhibit lower
396 running-induced knee loading than rearfoot strikers. *Med Sci Sports Exerc* 45: 2306-
397 2313. DOI: 10.1249/MSS.0b013e31829efcf7
- 398 28. Bonacci J, Vicenzino B, Spratford W, Collins P (2014). Take your shoes off to reduce
399 patellofemoral joint stress during running. *Br J Sports Med* 48: 425-8.
400 DOI:10.1136/bjsports-2013-092160.
- 401 29. Sinclair J (2014). Effects of barefoot and barefoot inspired footwear on knee and
402 ankle loading during running. *Clin Biomech* 29: 395-399. DOI:
403 10.1016/j.clinbiomech.2014.02.004

404

405 **Figure labels**

406 Figure 1: Patellofemoral force (a.), stress (b.) and (c.) sagittal plane knee angle as a function
407 of chainring geometry.

408 Figure 2: Comparison of patellofemoral force (a.), stress (b.) and (c.) sagittal plane knee
409 angle between conditions, positive values indicate that the round chainring values exceed
410 those in the oval condition (SPM (t) denotes the t value and critical thresholds for statistical
411 significance are denoted via the horizontal dotted lines).

412 Figure 3: Knee extensor kinetics (a.), rectus femoris (b.), vastus lateralis (c.) and vastus
413 medialis (d.) vastus intermedius as a function of chainring geometry.

414 Figure 4: Comparison of rectus femoris (a.), vastus lateralis (b.), vastus medialis (c.) and (d.)
415 vastus intermedius between conditions, positive values indicate that the round chainring

416 values exceed those in the oval condition (SPM (t) denotes the t value and critical thresholds
417 for statistical significance are denoted via the horizontal dotted lines).

418 Figure 5: Knee flexor kinetics (a.) semimembranosus, (b.) semitendinosus, (c.) biceps femoris
419 short head, (d.) biceps femoris long head, (e.) lateral gastrocnemius and (f.) medial
420 gastrocnemius as a function of chainring geometry.

421 Figure 6: Comparison of semimembranosus (a.), semitendinosus (b.), biceps femoris short
422 head (c.), biceps femoris long head (d.), (e.) lateral gastrocnemius and (f.) medial
423 gastrocnemius positive values indicate that the round chainring values exceed those in the
424 oval condition (SPM (t) denotes the t value and critical thresholds for statistical significance
425 are denoted via the horizontal dotted lines).

426 **Tables**

427 Table 1: Patellofemoral force per 20 km (Mean, SD & 95% CI) as a function of chainring geometry.

	Round			Oval			P-value	η^2
	Mean	SD	95% CI	Mean	SD	95% CI		
Patellofemoral force per 20 km (N/kg-s)	38576.40	10796.83	31716.42-45436.38	35637.00	8306.64	30359.21-40914.78	0.52	0.04

428

429