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1 **Studying mechanical load at body-seat interface during wheelchair**
2 **propulsion: A scoping review**

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10 Background: The increasing number of wheelchair users and their risk of medical
11 complications such as pressure ulcers (PU) make it important to have a better
12 understanding of their seating characteristics. However, while most studies tackling this
13 issue are based on static measurements, wheelchair users are active in their wheelchairs
14 when performing daily life activities. This suggests the need to assess the mechanical
15 loads at the wheelchair user's body – seat interface during dynamic activities.

16 Objectives: A scoping review was conducted to explore the existing data (shear load
17 and pressure) and highlight significant parameters, relevant conditions and
18 methodological strategies when studying wheelchair users performing a dynamic task.

19 Materials and methods: The literature search was performed by applying the PRISMA
20 methodology.

21 Results: 11 articles met the inclusion criteria. Differences between static and dynamic
22 data were found in the literature for peak pressure values, for pressure distribution and
23 in location of peak pressure. None measured tangential load at the seat/body interface,
24 although two studies measured the shift of the ischial region. A significant impact of
25 type of pathology has been quantified, showing the need to perform experimental

26 studies on diverse populations. The protocol and the pressure parameters studied were
27 very diverse.

28 Conclusion: Further studies carefully choosing interface pressure mapping parameters
29 and investigating a broader range of pathologies are required. Additionally, researchers
30 should focus on finding a way to measure seated tangential load.

31 Keywords: wheelchair; pressure; shear forces; dynamic.

32 IMPLICATIONS FOR REHABILITATION:

- 33 • When investigating forces at the body – seat interface during propulsion,
34 a large panel of patients suffering from different pathologies is needed.
- 35 • Measuring tangential load is complex and new tools are required for
36 measurements in the field.
- 37 • Participants' posture appears to be linked to forces at the body – seat
38 interface; this should be further investigated in dynamic conditions.

39 **Introduction**

40 Wheelchair user numbers are increasing with the improvement in life
41 expectancy [1]. In 2008, according to the World Health Organization (WHO), there
42 were 65 million wheelchair users worldwide [2], their prevalence varying
43 geographically: for example, 90.5 per 10,000 in the United States (users aged over 15 in
44 2002) and 62 per 10,000 in France (2008) [3,4]. More recently, in 2012 the Canadian
45 Survey on Disability reported approximately 1.5 million people using a mobility
46 assistive device (walker, wheelchair, scooter, etc.) [5].

47 The increasing number of wheelchair users [6] and their risk of medical
48 complications like pressure ulcers (PU) makes it important to have a better

49 understanding of their seating characteristics. Several epidemiological surveys reported
50 that more than 50% of wheelchair users in the United States developed at least one PU
51 in their life time [7,8]. Barrois et al. reported in a recent epidemiological survey that
52 42.4% of the patients suffering from PU in French public and private hospitals, care
53 units and nursing homes were wheelchair users [9].

54 The aetiology of pressure ulcers is multifactorial [10–13]. Classically, intrinsic
55 risk factors such as age, nutrition, immobility and sensory disorders are distinguished
56 from extrinsic risk factors such as temperature, humidity, contact surface and
57 mechanical factors. These mechanical conditions are defined by the type of mechanical
58 load (normal or shear forces). Several studies [14,15] showed the need to take into
59 account both pressure and tangential loads (shear), especially since shear stresses can
60 reduce the time required for PU onset [14]. Knowing the mechanical loads on the
61 wheelchair seat will therefore contribute to understanding the risk of PU for wheelchair
62 users.

63 PU prevention during wheelchair occupancy has been the subject of three
64 systematic reviews published since 2007 [16–18]. These reviews focus on static seating
65 conditions in a wheelchair, the most common seating conditions. Wheelchair users
66 spend on average 10.6 hours a day in their wheelchair [19,20], less than one hour of
67 which (11.2% of their wheelchair time) is spent moving forward over roughly 1.9km
68 [20], via either manual propulsion, electrical devices or being pushed.

69 There is international consensus on the fact that movement is key to prevention
70 of PU [21]. It is recommended that wheelchair users perform pressure relief manoeuvres
71 like push-ups [22]. Regarding locomotion, however, the link between mobility and PU
72 is unclear [23]. Do pressure peaks foster PU occurrence or, on the contrary, could the
73 generated variation in pressure help prevent PU? Furthermore, due to their rapid impact

74 on PU generation, dynamic shear forces also need to be investigated. In terms of PU
75 management, Damiao et al. [17] highlighted both the key role of cushions in static
76 conditions and the importance of wheelchair settings. Does the same apply to dynamic
77 conditions?

78 To help address these issues, this article presents a literature scoping review that
79 explores existing data on surface shear load and pressure measurements for wheelchair
80 users during mobility, aiming to supplement existing literature reviews on mechanical
81 load in static conditions. The results are analysed with reference to 1/ the population
82 studied, 2/ the protocol, 3/ the effects of cushions and wheelchair adjustments on PU
83 management, 4/ assessment tools and pressure analysis parameters and shear loads, 5/
84 the main findings from dynamic assessment studies.

85 **Method**

86 This scoping review follows the PRISMA methodology of Tricco et al. [24]
87 (www.Prisma-statement.org). To ensure the application of a rigorous protocol, the
88 recommendations by Arksey and O'Malley [25], adopted in another study [26], were
89 also taken into account.

90 *Literature search strategy*

91 The literature search was performed using PUBMED (1978 to January 2022)
92 and Web Of Science (1956 to January 2022) in February 2022 to find articles with an
93 available abstract. The following search terms were used: (pressure* OR shear* OR
94 tangential*) AND (wheelchair* OR seating*) AND (propulsion* OR locomotion*).

95 Two reviewers performed the literature search. The fields searched were title
96 and abstract. The eligibility and relevance of the articles were determined by reading the

97 abstracts. When there was any disagreement on inclusion or exclusion, the full article
98 was read and its inclusion discussed by the reviewers. The references of all selected
99 articles were also hand-searched for additional resources.

100 ***Eligibility criteria***

101 Articles were considered for inclusion if they contained pressure and/or
102 tangential load measurements at the body-seat interface during a dynamic task. Papers
103 were excluded 1/ if they reported only pressure or tangential load measurements
104 performed under static rather than dynamic conditions, 2/ if pressure and tangential load
105 were not measured at the human-seat interface, or 3/ if they were written in a language
106 other than French and English. Duplicates were removed.

107 Given the small sample of papers, the selection of sources of evidence was not
108 taken into account, as recommended by Arksey [25]; however, this point is discussed at
109 the end of the review.

110 ***Data extraction***

111 The two authors responsible for the literature search also extracted the data from
112 the selected articles. Data extraction items were first proposed by one reviewer, then
113 reviewed by the second reviewer. The final data table was built from the chosen data
114 items, and a descriptive analysis of the extracted data was carried out for each category
115 of item.

116 **Results**

117 ***Literature search results***

118 The initial database searches identified 128 articles which were further reduced

119 to 103 by removing duplicates. Application of exclusion criteria by reading the abstract
120 reduced the number of articles to 11. Analysis of the references of each included
121 publication failed to yield further relevant articles, and therefore the search procedure
122 identified a total of 11 articles meeting the inclusion criteria. Both reviewers found the
123 same number of articles and included the same 11 articles [27–37].

124 Results are summarised in Figure 1.

125 The data extraction items agreed on by the two reviewers were: authors, years of
126 publication, population (no. subjects, sex, weight, pathology), study design, assessment
127 system, propulsion mode (bi-manual, one arm – one leg, dual handrim, two legs
128 powered, etc.), type of wheelchair and adjustments, outcome parameters (such as peak
129 pressure, average pressure), dynamic analysis strategy, main results. There was no
130 disagreement between the reviewers on data extraction, both identifying the same data
131 for each item.

132 ***Population***

133 The clinical status of populations differed. Three studies [27,34,36] recruited
134 only able-bodied participants, with respectively 2, 19 and 1 participants. Two studies
135 [31,35] recruited both able-bodied and disabled participants, with respectively 20 (10
136 able-bodied, 10 SCI (spinal cord injury)) and 8 (1 SCI, 3 spina bifida, 2 orthopaedics, 1
137 amputee and 1 able-bodied) participants. The 6 other studies recruited only disabled
138 participants, with respectively 1 (cerebral palsy), 15 (SCI), 10 (SCI), 8 (6 SCI and 2
139 multiple sclerosis), 15 (hemiplegia) and 10 (SCI) participants [28–30,32,33,38]. More
140 details are available in Table 1.

141 ***Protocol***

142 Concerning study design, type of propulsion and type of wheelchair and
143 adjustment, nine studies [27–31,33,35,36,38] compared static and dynamic conditions
144 and two [32,34] compared different types of propulsion without static measurements.
145 The dynamic condition activity was bi-manual propulsion in 9 studies [27–31,33–35,38]
146 and one study [32] focused on 3 types of propulsion for hemiplegic users (one-arm
147 lever-driver, dual handrims and a novel device consisting of 1 handrim with 1 foot for
148 direction (Neater®)).

149 Some protocols were laboratory-oriented, with wheelchairs placed on
150 ergometers for easy measurement control [27,31,35,38]. Others reproduced daily
151 situations, with a setup of self-propelled courses either in a direct line of 3 metres [36],
152 10 metres [34], 15.2 metres [28,29], 100 metres [33] or during 5s [30], and an indoor
153 circuit [32].

154 *Cushion characteristics and wheelchair adjustments*

155 Supports, such as the cushion, varied widely. Three studies used no specific
156 support; participants sat directly on the wheelchair seatpan [27,31,34]. Three used a
157 single cushion appropriate to the user's needs [28,29,32] and the last 4 studies compared
158 different cushions in their protocol [30,33,35,38].

159 In five studies, participants used their personal wheelchair with their personal
160 wheelchair adjustments [28–30,33,38]. Four studies used the same wheelchair for all
161 participants, adjusting the size but keeping all the other parameters (such as tilt or
162 backrest inclination) the same for each participant [27,31,34,39]. This information was
163 not found in two studies [35,36].

164 *Assessment tools and pressure analysis parameters and shear loads*

165 Assessment tools and pressure parameters (Table 1) showed major technological
166 discrepancies. Two studies measured the force under the seatpan using force sensors
167 [27,38], some of which were placed in specific areas in the seatpan, with one additional
168 sensor to cover the entire seatpan. However, most studies used pressure maps to obtain
169 more precise data on pressure distribution [28–31,33–36,39]. All parameters exported
170 from pressure maps in the different studies are summarised in Table 1.

171 The definition of peak pressure differed from one study to another (varying
172 according to pressure map resolution), preventing us from comparing these results.
173 Another outcome called peak pressure index left/right (the sensor average within a
174 10 cm² window of the peak pressure sensor) was used to target the ischial tuberosity in
175 one study [33].

176 *Main findings in dynamic assessment studies*

177 Data processing took different forms under dynamic conditions. Two studies
178 measured the shift of the ischial tuberosities during wheelchair propulsion. The others
179 used pressure map parameters: some examined the parameter minimum and maximum
180 measurements over recordings [27,31,36,38], while others used the mean recorded for
181 each measured parameter [28–31,33–35,39].

182 The main findings from dynamic assessment were as follows. Some articles noted
183 differences between static and dynamic data: Table 2. Parameters studied in the selected
184 literature and their dynamic/static ratio either discrepancies in peak pressure, with
185 differences in minimum and maximum variation (from 30% to 230% of static values)
186 [27,36], in mean value (from 76% to 112% of static values) [28,31,36] and in location
187 of peak pressure (24 mm between pic and IT location for the SCI population and 13 mm
188 for the able-bodied population) [31].

189 Other articles noted differences in activities' impacts on pressure distribution
190 [32,33] and on its magnitude [36,38]. For example, unilateral propulsion with a dual
191 handrim induces more forces (494.43 N) on the ipsilateral side of the seat than with a
192 lever arm (368.05 N). Details are shown in Table 1, Table 2 and Table 3.

193 Regarding tangential load, none of the 11 studies measured it at the body-seat
194 interface. However, 2 articles [31,34] attempted to reveal tangential loads through the
195 shifting of the ischial areas. Tam et al. explored ischial tuberosities' location and shift in
196 dynamic conditions [31]. Uemura et. al designed a protocol to assess the ischial area
197 shift during activity but did not calculate the shear stress associated with this motion
198 [34]. Thus, while there is evidence of this cycling ischial shift, no data are available to
199 quantify the associated tangential load.

200 **Discussion**

201 One of the main findings of this review is the absence of standards for the
202 assessment of forces at the body-seat interface of a wheelchair user performing a
203 dynamic task.

204 ***Population***

205 Four of the 11 studies were single-participant case studies [27,35,36,38]. The
206 number of participants in the other studies ranged from 8 to 20, enabling statistical
207 analyses: for instance, comparing body-seat interface measurements performed under
208 static versus dynamic conditions [28,30], comparing different surface materials [29,33],
209 types of activities [32] or population characteristics [31]. One study using various
210 participant typologies had a number of participants per typology that resembled a case
211 study [35], weakening the statistical interpretation of the results in terms of pathology.

212 Since pathologies can affect tissue morphology and pressure distribution [40],
213 the differing participant characteristics in these studies make it difficult to draw general
214 conclusions. The pathologies represented were mainly pathologies causing paraplegia or
215 tetraplegia, with sensory disorders. These pathologies represent the disability group
216 with highest PU prevalence (23%) [41]. Only two studies included pathological
217 participants without sensory disorders (Cerebral Palsy, amputee) [38,39]. This
218 difference between participants concerning sensory disorders could influence the load
219 distribution at the body-seat interface, and limits further analysis.

220 *Protocol*

221 Bimanual propulsion was the propulsion mode most commonly studied
222 [30,34,35,37–40,42,43]. Only one study tried to explore one-sided propulsion for
223 hemiplegic users [39]. There was no examination of certain propulsion modes, like
224 bipodal propulsion. The wide variety of study designs prevents any precise comparison.

225 To capture the actual pressures that wheelchair users are subjected to on a day-
226 to-day basis, pressure distribution should be studied during daily life activities. Even
227 protocols attempting to more faithfully replicate daily activities only asked participants
228 to roll along a straight line for 3 to 100 metres [35,36,39,40,42,43], which is not
229 representative of daily life wheelchair propulsion. Sonenblum and al. pointed out that
230 63% of wheelchair bouts of mobility covered less than 12.5 m at less than 0.5 m/s [20].
231 The indoor circuit for hemiplegic users [39] seems to represent an institutional kind of
232 wheelchair propulsion more than real daily life wheelchair propulsion [20].
233 Furthermore, measurements are not made on a variety of ground surfaces representing
234 the full range of propulsion conditions.

235 *Cushion characteristics and wheelchair adjustments*

236 An important finding of this review is the confirmation that a cushion offers the
237 same spatial pressure distribution under both static and dynamic conditions. All studies
238 comparing cushions found similar differences in spatial pressure distribution between
239 cushions tested under static and dynamic conditions [37,38,42,43]. Thus, when selecting
240 the most suitable cushions, a static evaluation may be sufficient.

241 However, wheelchair adjustment does not yield information on the participants'
242 posture in their wheelchair, which makes it difficult to compare participants. Indeed,
243 pelvic position (tilt, inclination) leads to different load distributions [44,46]. Many
244 studies do not provide any information about wheelchair adjustments and the nature of
245 assistive postural devices (such as a backrest) [27–30,33–36,38,39]. This lack of
246 information also limits opportunities for cushion comparison. The cushions are
247 documented as efficient in terms of pressure distribution, with a backrest adjustment to
248 control pelvis tilt position [47].

249 *Assessment tools and pressure analysis parameters and shear loads*

250 The major technological disparities among the sensors used in the selected
251 studies make it impossible to compare the absolute values of their outputs. A pressure
252 mapping system with reasonable resolution should be used. At least 1024 sensors over
253 42*42 cm² is precise enough to target the IT area, with the peak pressure index
254 indicating the region most at risk of PU [10]. Seven studies met this resolution criterion
255 [28–31,33,36,39] of at least 0.5 sensor per cm², and 3 provided better resolution, with 1
256 sensor per cm² [30,31,36].

257 None of the studies provided information on the calibration of the pressure
258 mapping system, nor on the lapse of time between being seated on the cushion and

259 measurement. More reliable data is known to be obtained from measurements taken at
260 the body-cushion interface several minutes after the user is seated, due to cushion
261 sagging [42,43].

262 There was only one point of convergence concerning the outcome parameters:
263 all focused on peak pressure. However, as its definition differed from one study to
264 another, peak pressure results cannot really be compared. The recent outcome peak
265 pressure index left/right has been documented by Hobson and al. [44] as targeting the IT
266 area. We therefore recommend using it to define peak pressure for the ischial tuberosity
267 area, since this parameter would be less sensitive to erroneous data points. In addition,
268 being computed on a given area, this parameter facilitates comparison between values
269 obtained at different pressure map resolutions. Another interesting outcome parameter is
270 spatial average pressure (pressure averaged over all the pressure map sensors), which
271 seems preferable to total normal force because it uses the same unit as for peak pressure
272 (spatial pressure). This would enable the peak/average ratio to be studied, allowing a
273 better understanding of the PU risk than peak values alone. The location of the peak
274 pressure index as a function of time is another useful outcome parameter that can bring
275 to light an anterior shift of the ischial tuberosity area during propulsion [34]. The
276 sensitivity of IT shifting is likely of the same order of magnitude as the resolution of the
277 pressure map, which is why we recommend a pressure map resolution of 1024 sensors
278 per 42x42 cm² minimum.

279 *Main findings in dynamic assessment studies*

280 Currently, with PU injury thresholds at the body-seat interface not known,
281 conclusions cannot be drawn on the risk of PU occurrence, even when static conditions
282 are compared to dynamic conditions. Approaches linked to modelling could make it

283 possible to move towards an estimation of lesion thresholds [15].

284 Values for peak pressure or average pressure in dynamic mode are cyclic during
285 bimanual propulsion [28,30,36,38]. Our interpretation of this variation is that the cyclic
286 load applied to handrims unloads the seating area. In addition, the movement of the
287 trunk and arms implies that the centre of gravity shifts on the seat in a cyclical manner,
288 together with peak pressure values.

289 The higher peak values found in dynamic than in static mode in other studies
290 [27,31] confirm the difference in pressure between static and dynamic conditions,
291 raising questions about the impact of these differences on overall pressure distribution.
292 Unfortunately, in the only study extending the analysis from external forces to internal
293 forces, the ratio between internal pressure (fat and muscle) and external pressure was
294 not provided for dynamic conditions [36].

295 As for the vertical reaction force measured in the study on one-arm drive
296 wheelchairs, the differences between right and left side highlight the difficulty of
297 propelling a wheelchair with one side of the body. Indeed, the increased load on the
298 driver side of the seat suggests that participants leaned on their unimpaired side to
299 stabilise their pelvis in the wheelchair and increase their power for wheelchair
300 propulsion. The degree to which they bent over reflects the degree of difficulty of the
301 wheelchair movement: bending over compensates for a more difficult propulsion mode
302 or a more challenged wheelchair user [45]. Propelling the wheelchair required the use of
303 both their trunk weight in front of the ischial tuberosity zone to stabilise the pelvis and
304 their body weight to increase arm strength. Although the study of Mandy and al.
305 focused on a facilitating device (Neater) [39], their result cannot be generalised to all
306 patients. Hemiplegia is a complex disability with multiple secondary disorders and the

307 most important parameter for the user is being able to use the wheelchair, even when
308 this is challenging.

309 Regarding data processing, the two approaches (looking at variations and/or the
310 average of the recording for each parameter chosen, like peak pressure, mean pressure,
311 etc.) observed in all the studies are relevant, and when combined yield a more thorough
312 assessment of the propulsion task. The recording average provides the overall outcome
313 of the experiment, which may be enough in cases where the aim is not to study the
314 forces from a biomechanical point of view [33,35].

315 In contrast, when the goal is the biomechanical study of the forces during
316 propulsion for a better understanding of the task, looking at both the average (temporal)
317 and variations during the activity is more appropriate [31,36,38]. Since the location of
318 the peak pressure index is a relevant representation of the shift of the ischial tuberosity
319 area, we suggest that studying peak pressure index recordings as a function of time
320 better reveals the biomechanics of a dynamic task [27,31,36,38]. This kind of analysis
321 is, however, difficult to perform in the field due to the high number of parameters to be
322 recorded (several propulsion cycles in a framed environment are required to perform
323 biomechanical analyses such as motion analysis and inverse kinematics and dynamics).

324 In static conditions, tangential loads at the body-seat interface have mainly been
325 studied in laboratory conditions [44,48,49], since shear sensors have several limitations
326 that compromise their use in everyday conditions. The reviewers did not find any
327 mention of tools that might enable tangential load to be measured or estimated at the
328 body-seat interface in everyday conditions [44,48,49]. Technical issues may be
329 involved: a major constraint is the thickness (e.g. Predia® sensors) and rigidity (e.g.
330 force plate) of the sensor, making it inappropriate for evaluations at the body-seat

331 interface for wheelchair users who need cushions to prevent PU. A second constraint is
332 the fact that these sensors are not easily transportable (no wireless connection or
333 cumbersome), reducing their usefulness for prolonged recording in daily life [44,48,49].

334 Thus, the reviewers did not find any study measuring antero-posterior tangential
335 load in dynamic conditions. Nevertheless, two studies highlighted the existence of
336 tangential load by measuring the shift of the ischial tuberosity area over time. However,
337 their measurements were not used to predict any values to compare participants and/or
338 force conditions [31,34]. Loerakker's work on the aetiology of pressure ulcers
339 confirmed the role of both normal and tangential loads in PU occurrence [10]. As for
340 prosthetics applications [50], a tool for measuring seated tangential load in dynamic
341 conditions needs to be developed, for a better understanding of the role that both normal
342 and tangential loads at the body-seat interface play in PU during a dynamic task like
343 wheelchair propulsion. Tangential load measurements could reveal major differences
344 between dynamic and static conditions. Furthermore, finite element analysis could shed
345 light on shear forces both at the body – seat interface and at the ischial tuberosity
346 interface during wheelchair propulsion [51]. Since studies on animal models have
347 revealed that shear forces double the PU occurrence for the same normal mechanical
348 load [52], a numerical approach might be a good starting point.

349 **Limitation and conclusion**

350 One of our objectives here was to highlight relevant conditions and
351 methodological strategies to study tangential load and pressure distribution at the body-
352 seat interface during propulsion in wheelchairs. Overall, the existing literature shows a
353 lack of consensus, although some conclusions can be drawn from this scoping review.
354 There are not enough dynamic studies for any extrapolation that would allow static and

355 dynamic conditions to be compared under a single experimental procedure.

356 From the point of view of study participants, a significant impact of type of
357 pathology has been quantified, showing the need to perform experimental studies on
358 diverse populations. However, this impact is of the same order of magnitude under both
359 static and dynamic conditions. Participant posture will influence seat pressure
360 distributions, so that describing these distributions will shed light on the differences
361 between participants. In addition, cushion characteristics can influence participant
362 posture and therefore change pressure distribution.

363 **Future research**

364 There is a clear need for more dynamic studies of wheelchair users for a better
365 understanding of normal mechanical loading in dynamic sitting. Moreover, better
366 assessment of tangential load could be achieved by measuring the shift in ischial
367 tuberosities and/or directly measuring the force with new tools. Such studies should
368 carefully choose pressure map parameters and adopt an innovative approach to study
369 tangential load under dynamic conditions, without neglecting participant posture.

370 These findings confirm the conclusions of Bader et al.'s systematic review
371 highlighting the need to develop an integrated system to monitor both mechanical loads
372 [15]. The recent progress in the development of machine learning algorithms or the use
373 of artificial intelligence could enhance PU management by better reflecting daily life, as
374 already achieved for wheelchair users' posture guidance and for continuous pressure
375 monitoring [53,54].

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378 **Disclosure statement**

379 Two of the authors are employed by Taxisense, a company producing textile sensors
380 which partially funded this study.

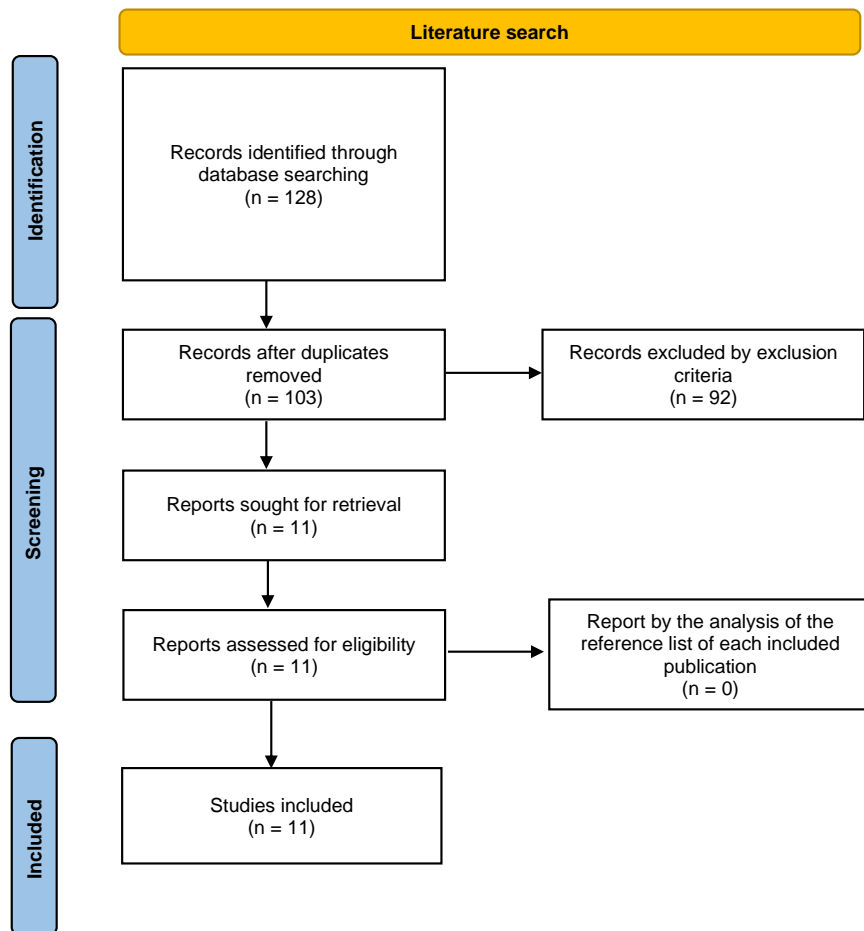


Figure 1. Flow diagram of study selection procedure

381
382

Ref.	Population (no. subjects, sex, weight, pathology)	Study design	Assessment tools	Propulsion mode	Type of wheelchair and adjustments	Outcome parameters	Data processing in dynamic conditions	Main findings in dynamic assessment studies
Eckrich	N = 2 Able-bodied	Bimanual propulsion over 8m,	50 sensors (5*10) over half the surface frequency: 10 Hz	Bimanual	Identical wheelchair for everyone tilt: 10 °, backrest inclination 14°	Centre of pressure Right/Left Average pressure Right/Left Maximum pressure Right/Left Area above 35 mmHg	Min and max of the curb	Highlighting additional pressure stress on the buttocks during manual propulsion
Dabnichki and Taktak	N= 1 Cerebral Palsy	Bimanual propulsion on ergometer for 10s 3 cushion fabrics 4 speeds 5 trials	Force sensors under both ischial regions (PEDAR®) Force plate under the seat	Bimanual	Personal wheelchair with tilt of 7°	Vertical force Pressure under IT	Min and max of the curb	The dynamic load acting on the seating area during propulsion exceeded body weight The force gradients were very high, Cushion material response should be tested under realistic dynamic conditions
Kernozek et al.	N=15 (2w, 13m; 77.5 +/- 22.4Kg) SCI	Bimanual propulsion over 15.2m Evaluation of 3 cycles at constant speed: 1.3m/s 4 trials Comparison static versus dynamic	Pressure mapping: Novel Pliance System™, 32*32 (1024 sensors) Frequency: 10Hz Resolution 0.1 N/cm²	Bimanual	Personal Wheelchair with Jay active cushion	Peak pressure Pressure time integral	Mean over participants	Peak pressures were greater during propulsion (up to 42%) Cumulative effect of loading was comparable in static or dynamic conditions
Kernozek et al.	N = 10 (2w, 7m; 76.2 +/- 23.1.4Kg) SCI	Bimanual propulsion over 15.2m Evaluation of 3 cycles at constant speed: 1.4 m/s 3 trials, 3 conditions	Pressure mapping: Novel Pliance System™, 32*32 (1024 sensors) Frequency: 10Hz Resolution 0.1 N/cm²	Bimanual	Personal wheelchair with 3 test cushions: 2'' foam, Jay active (gel) and Roho Low Profile (air)	Peak pressure Dynamic Pressure Fluctuation (average maximum peak pressure - average minimum peak pressure)		Average pressure fluctuated according to cushion type (Roho Low profile and Jay Active absorbed more pressure than the Foam cushion)

		Comparison of 3 cushions						
Andreoni et al.	N = 8 (2w, 6m; 68 +/-9.2Kg) 6 SCI lacking sensitivity in lower limbs 2 MS with sensitivity in lower limbs	Bimanual propulsion for 5s Comparison static versus dynamic	Pressure mapping: Tekscan™, 42*48 (2016 sensors) Frequency: 10Hz, Resolution: 1 sensor per cm ²	Bimanual	Personal wheelchair 0° tilt 0° to 10° backrest inclination depending on participant comfort	Average pressure over the map Peak pressure Surface	Mean over participants	Mean pressure decreased during propulsion whereas peak values increased
Tam et al.	N= 20 10 Able-bodied 10 SCI	Bimanual propulsion on ergometer 5 trials Backrest modification for Vicon marker visualisation Motion capture and pressure evaluation Ischial region identification before the test Comparison static versus dynamic	Pressure mapping: Tekscan™, 42*48 (2016 sensors) Frequency: 10Hz, Resolution: 1 sensor per cm ²	Bimanual	Wheelchair QuickyLife without cushion	Average pressure under the IT Peak pressure under the IT Location of the IT	Mean, Min and Max over participant Left/Right	Peak pressure magnitude varied up to 310% and 75% in normal and SCI participants, respectively IT were located 19.2 ± 11.7mm behind peak pressure location

Hollington et al.	N = 8 (2w, 6m) SCI 1 Spina Bifida 3 Orthopedic 2 Amputee 1 Able-bodied 1	Bimanual propulsion on ergometer for 30s in high speed 3 trials 4 cushions Static and dynamic for each cushion Recording time: 10s	Pressure mapping: Vista Medical® 16*16 (256 sensors) Frequency: 10Hz, Resolution: 0.3 sensor per cm ²	Bimanual	No information	Pressure under the IT (defined as a 4-sensor area)	Mean over 3 trials per participant	Cushion ranking by mean pressure under IT was not influenced by dynamic conditions
Mandy et al.	N= 15 14 Left hemiplegia 1 Right hemiplegia	3 different propulsion modes over a course 1 trial 3 conditions (lever wheelchair, dual-handrims wheelchair and Neater Uni-wheelchair)	Pressure mapping: CONFORMAT® (Tekscan), 32*32 (1024 sensors) Frequency: 10 Hz Resolution: 0.5 sensor per cm ²	Unimanual and mixt	Same wheelchair for every participant 3 different wheelchairs according to propulsion mode	Total normal force from half-seat	Left/Right	Right/Left Vertical reaction force distribution increase on the propulsion side for Neater and dual-handrims propulsion Dual-handrims propulsion led to a significant improvement in vertical reaction force on both sides compared to the other propulsion modes
Li et al,	N = 1 Able-bodied	2 different speeds (0,3m/s and 0,6 m/s) in static conditions FE model validation	Pressure mapping: ClinSeat Type 5315 Sensor (Tekscan™), 42*48 (2016 sensors) Frequency: 10Hz, Resolution: 1 sensor per cm ²	Bimanual	No specific information	Peak Pressure (left and right)	Max of the curb and the curb (left/right)	Peaks of pressure were greater at a faster speed and higher than in static conditions Simulated peak in Fat or Muscle tissue increased in dynamic conditions and with speed

Mendes et al.	N = 10 (4w, 6m; 68.5 +/- 9.51Kg) SCI Paraplegia 5 Tetraplegia 5	Bimanual propulsion or pushing over 200m (round trip) Cushion comparison (Roho Quadro, Jay air, Varilite, personal) Comparison static versus dynamic	Pressure mapping: Xsensor®, 36*36 (1296 sensors) Frequency: 45Hz Resolution: 0.5 sensor per cm ²	Bimanual	Personal wheelchair	Mean pressure Peak pressure Contact area Peak pressure index (PPI, the sensor average within a 10 cm ² window of the peak pressure sensor)	Mean over participants	PPI _{max} increased in dynamic conditions with a Roho Quadro, but not with the other cushions
Uemura et al.	N = 20 (10w, 10m; 53.1 +/- 5.04Kg) Able-bodied	Bimanual propulsion on a standard WC over 10m 3 times Electric WC right joystick, 3.8 km/h over 10m 3 times	Pressure mapping: (Takano), 16*16 (256 sensors) Frequency: 5 Hz Resolution: 0.3 sensor per cm ² Side camera	Bimanual Electric	Same Electric WC 2 MWC to fit participant morphology	Maximum pressure region location	Mean over participants	Ischial region shifted while manoeuvring a wheelchair in both propulsion modes

Table 1. Summary of contents of studies by data item

Parameter	Ref.	Dynamic/Static ratio
Min mean spatial pressure	Eckrich	0.5
Max mean spatial pressure	Eckrich	1.3
Average mean spatial pressure	Andreoni et al.	0.92
	Hollington et al.	0.78 - 1
	Mendes et al.	1.06 - 1.12
Average peak pressure (peak, PPI ...)	Tam et al.	0.76 - 0.9
Min peak pressure (peak, PPI ...)	Eckrich	0.3
Max peak pressure (peak, PPI ...)	Eckrich	2.3
	Kernozek et al.	1.25
	Andreoni et al.	1.42
	Mendes et al.	0.97 - 1.34
Min total Force	Dabnichki and Taktak	0.41 - 1.24
Max total Force	Dabnichki and Taktak	1.24 - 1.96

Table 2. Parameters studied in the selected literature and their dynamic/static ratio

Ref.	Eckrich	Dabnichki and Taktak	Kernozeq et al.	Kernozeq et al.	Andreoni et al.	Tam et al.	Hollington et al.	Mendes et al.
Participants	N = 2	N= 1	N=15	N = 10	N = 8	N= 20	N = 8	N = 10
Propulsion	bi-manual	bi-manual	bi-manual	bi-manual	bi-manual	bi-manual	bi-manual	bi-manual
Static								
Mean spatial pressure	3.7 kPa				3.12 kPa		Cushion: Polyfoam/Viscoelastic/ Gel Insert/Air Insert amputation: 8.4 kPa / 10.36 kPa / 9.06 kPa / 9.72 kPa spina 1: 6.34 kPa / 7.67 kPa / 5.73 kPa / 5.97 kPa spina 2: 13.22 kPa / 12.58 kPa / 9.51 kPa / 9.01 kPa able bodied: 9.65 kPa / 10.06 kPa / 7.94 kPa / 7.22 kPa	Roho/Jay/Varilite/personal Paraplegic: 5.08 kPa / 5.02 kPa / 5.23 kPa / 6.33 kPa Tetraplegic: 5.69 kPa / 5.64 kPa/ 6.01 kPa / 5.87 kPa
Total normal force		Seatpan Rigid: 472N Rubber mat: 496N Soft mat: 499N						
Peak sensors	18 kPa	Right / left Rigid: 8 kPa / 5,3 kPa Rubber mat: 4.5 kPa / 2,3 kPa Soft mat: 1.7 kPa / 1,3 kPa	16,2 +/- 5 kPa			Right/Left Able-bodied: 49 kPa / 48.12 kPa SCI: 58.57 kPa / 59.2 kPa		Roho/Jay/Varilite/personal Paraplegic: 22.22 kPa / 23.26 kPa / 25.89 kPa / 28.45 kPa Tetraplegic: 22.81 kPa / 31.01 kPa / 28.36 kPa / 19.82 kPa
mean IT pressure / PPI index	min: 4 kPa max: 30 kPa					Right/Left Able-bodied: 16.46 kPa / 16,81 kPa SCI: 18.45 kPa / 17.45 kPa		Roho/Jay/Varilite/personal Paraplegic: 14.89 kPa / 13.43 kPa / 19.36 kPa / 21.66 kPa Tetraplegic: 14.76 kPa / 20.29 kPa / 22.37 kPa / 14.73 kPa
Dynamic								

Mean spatial pressure	Min: 1.89 kPa Max: 4.87 kPa	average: 2.8 kPa	Cushion: Polyfoam/Viscoelastic/ Gel Insert/Air Insert amputation: 7.21 kPa / 9.27 kPa / 7.81 kPa / 8.02 kPa	Roho/Jay/Varilite/personal Paraplegic: 5.64 kPa / 5.51 kPa / 5.69 kPa / 6.85 kPa
			spina 1: 5.87 kPa / 6.99 kPa / 5.03 kPa / 5.08 kPa	Tetraplegic: 6.37 kPa / 5.97 kPa / 6.51 kPa / 6.56 kPa
			spina 2: 12.4 kPa / 11.07 kPa / 9.29 kPa / 8.80 kPa	
			able-bodied: 8.57 kPa / 8.16 kPa / 6.18 kPa / 5.87 kPa	
Max total normal force	Speed: Slow/Medium/Fast/max Rigid: 3.1kPa / 3,3 kPa / 3,4 kPa/ 4kPa Rubber mat: 3.4 kPa/ 3.9kPa / 4.7kPa / 4.9kPa Soft mat: 3.6kPa / 3.6kPa / 4.6kPa / 5.7kPa			
Min total normal force	Speed: Slow/Medium/Fast/max Rigid: 2.2 kPa / 1.2 kPa / 1.16 kPa / 0.38kPa Rubber mat: 2.17 kPa / 1.43 kPa / 1.32 kPa / 0.91 kPa Soft mat: 2.49 kPa / 1.57 kPa / 1.08kPa / 0.65kPa			
Average peak		20.3 +/- 6.6 kPa	Right/Left Able-bodied: 14.22 kPa / 12.85 kPa SCI: 14.65 kPa / 16 kPa	
Min peak	5.6 kPa			

Max peak	23.8 kPa	Speed: Slow/Medium/Fast/max Rigid: Right 7.4 kPa / 8.3 kPa / 7.8 kPa / 4.5kPa Left: 5.8 kPa / 6 kPa / 4.1 kPa / 4.5 kPa Rubber mat: Right: 5.7 kPa / 6 kPa / 3.4 kPa / 2.8 kPa Left: 4.4 kPa / 4.5 kPa / 3 kPa / 2.9 kPa Soft mat: Right: 1.7 kPa / 1.6 kPa / 1.6 kPa / 1.6 kPa Left: 1.6 kPa / 1.4 kPa / 1.6 kPa / 1.6 kPa	21.15 kPa	Right/Left Able-bodied: 46.14 kPa / 55.46 kPa SCI: 59.5 kPa / 59.94 kPa	Roho/Jay/Varilite/personal Paraplegic: 25.84 kPa / 7.99 kPa / 26.26 kPa / 30.44 kPa Tetraplegic: 24.12 kPa / 30.13 kPa / 30.13 kPa / 21.60 kPa PPI Paraplegic: 16.65 kPa / 14.52 kPa / 19.55 kPa / 24.60 kPa Tetraplegic: 19.80 kPa / 21.09 kPa / 22.37 kPa / 15.59 kPa
PPI index		Fluctuation (min-max) Foam: 97 +/- 44 kPa Jay: 50.2 +/- 15.1 kPa Roho: 44.8 +/- 20.8 kPa			

Table 3: Parameters and their values in different conditions for each study

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