

1 **Neck Brace Design and Fit are Linked to Head Mobility**

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3 Beauséjour, Marie-Hélène (1,2); Bailly, Nicolas (2); Wei, Wei (2); Llari, Maxime (2); Morgane Evin (2);
4 Panichelli, Paolo (2); Arnoux, Pierre-Jean (2)

5 **Authors affiliation**

6 (1) École de technologie supérieure (Department of Systems Engineering), Montréal (Québec),
7 Canada

8 (2) Aix Marseille Univ, Univ Gustave Eiffel, LBA, Marseille, France

9 **Corresponding author:**

10 Marie-Hélène Beauséjour,

11 marie-helene.beausejour@etsmtl.ca

12 ORCID: 0000-0001-5720-3712

13 Abstract

14
15 Karting can lead to head impact and cervical spine injuries. To mitigate the risks, drivers wear neck
16 braces. However, little is known of their efficacy and little information is available to help drivers select
17 the optimal neck brace. This study aimed to measure the head mobility and drivers' field of view
18 associated with six different neck brace models and the correlations between neck brace design and
19 fitting and mobility. The head mobility of twenty volunteers seated in a kart was measured in the three
20 anatomical planes using an optoelectronic system. The anterior and posterior gaps between the neck
21 braces and helmet were measured. Finally, the neck braces were put on an anthropometric dummy
22 and measurements were taken on the neck brace at points of contact between the neck brace and the
23 helmet. All neck braces reduced the head mobility with axial rotation being the least restricted
24 direction. Only the soft neck braces influenced the field of view. The mobility in lateral bending and
25 extension were strongly correlated to the neck brace design (Pearson R Coefficient of 0.997 and 0.96).
26 The posterior gap was also correlated to extension mobility. Therefore, neck brace design and fitting

29 Introduction

30
31 Karting is a recreational and professional sport, and the FIA karting championships welcome drivers
32 from the age of twelve [1]. Karting accidents resulted in severe injuries since the karts are fast and
33 their design offers minimal protection for the drivers [2]. High-energy trauma due to karting was
34 mostly caused by frontal impacts between the cars or with the guardrail [2]. In Australia, ten deaths
35 were reported between 2000 – 2007, but the injury mechanisms were not discussed except for one
36 open coronial case [3]. In the United States, 231 deaths due to go-kart accidents were reported
37 between 1985 and 1996 [4]. The main causes of death were head impacts and neck fractures.

38 Neck braces were designed to mitigate the risk of neck injury by creating an "alternate load path" away
39 from the cervical spine for the impact load and limit non-physiological range of motion (ROM) [5].
40 However, the evaluation of neck brace efficacy in the literature has been limited and there is no
41 regulation standard for neck brace design. Leatt, de Jongh, and Keevy [5] performed experimental tests
42 on Hybrid III dummies wearing neck braces, frontal sled tests and pendulum tests, but the
43 experimental data analysis was focused on the head and neck motion and loads in the sagittal plane.
44 Researchers measured the influence of a neck brace on neck loads using anthropometric test dummies
45 during "near" vertex impacts [6] and during inverted pendulum tests [7] applying compression-flexion,
46 tension-flexion and tension-extension loads to the neck. However, in these two studies, only one brand
47 of neck brace was used.

48 A few studies have utilized human body models [8–11] to analyze the head motions and the loads at
49 the cervical spine for different head impact scenarios and with different neck brace models. However,
50 while these studies enabled traumatic analyses and access to results that are difficult to measure
51 experimentally, they used standard-size human models (50th percentile), which do not consider inter-
52 individual differences. Correctly modelling the interaction between the driver, the neck brace and the
53 helmet is also challenging, and no validation data were used.

54 Considering motion restriction as a key point for injury mitigation, while many studies were conducted
55 on the physiological ROM of the head [12–14], only a few studies have been done on head mobility
56 with a helmet or neck brace. Gorasso et Petrone [15] measured head ROM with and without a neck
57 brace and head mobility during a motocross circuit, but they tested only one model of a neck brace.
58 Hurst et al. [16] measured head accelerations and angular velocity with and without a neck brace
59 (three different models) on a BMX track, but the reported data are difficult to apply to traumatic cases.
60 Lecouplet et al., [17] measured the head rotations and translations of volunteers wearing a motorcycle
61 helmet, but no neck brace. Head ROM between drivers on a scooter or on a motorcycle using four
62 different types of neck brace were measured [18]. The authors concluded that the driver’s posture has
63 a significant impact on neck ROM.

64 Seating in a kart, the driver’s hips are in retroversion, and the spinal curvatures (lordosis and cyphosis)
65 are, therefore, different from sitting in a chair or in a car [19, 20]. No study has been done on the head
66 mobility allowed by commercial neck braces while in a driving position in a kart, and these studies have
67 not reported the influence of the neck brace on the drivers’ field of view. Considering the field of view
68 for the driver’s comfort and safety is important. Furthermore, the influence of the neck brace fit or its
69 design on movement restriction has not been evaluated. These elements would be of interest for
70 equipment designers and protection standards evolution.

71 This paper aimed to measure the restriction of the head ROM with different models of neck braces
72 (motorcycles and karting neck braces) on healthy volunteers seated in a kart. It was hypothesized that
73 the fitting and the design of the neck braces would be correlated with the head ROM.

74

75 **Keywords**

76 Neck brace, karting, motorcycling, mobility, protective devices

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78 **Methods**

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80 **Participants**

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82 Twenty participants were recruited for this study. Their age, gender, height, mass, body mass index
83 and number of hours of physical activity per week are given in Table 1. The participants were between
84 20 and 43 years old. Twelve were males (eight females), and their mean height and mass were $174 \pm$
85 10 cm and 68 ± 12 kg, respectively, which was close to the height and mass of a 50th male: 174.9 cm
86 and 78.6 kg [21]. The research protocol was approved by the Comité de protection des personnes Sud-
87 Est VI under reference 2021-A03174-37. All participants provided informed written consent to be part
88 of this study.

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Table 1 - Volunteers anthropometric information and number of hours of physical activity per week

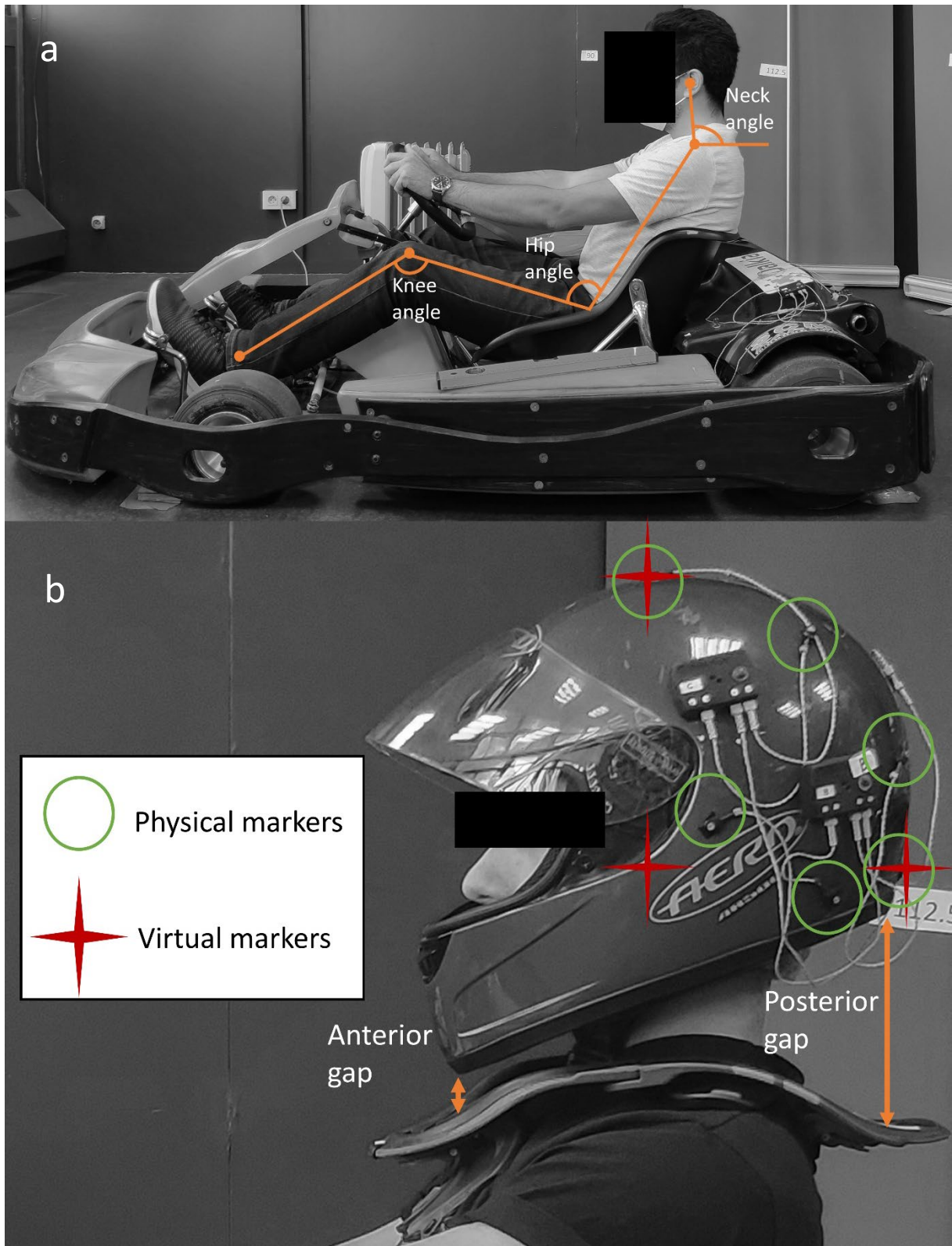
Volunteer ID	Age	Gender	Height (cm)	Mass (kg)	Body mass index	Number of hours of physical activity per week
0	31	M	165	65	24	5
1	31	F	170	70	24	11
2	24	M	187	74	21	5.5
3	30	F	163	54	20	8
4	29	M	182	82	25	0
5	20	M	180	71	22	3
6	22	M	186	71	21	15
7	43	M	186	80	23	2
8	23	F	162	58	22	1.5
9	27	M	185	75	22	6
10	23	F	160	57	22	3
11	32	M	170	72	25	0
12	26	M	185	85	25	15
13	22	F	160	53	21	2.5
14	27	F	160	50	20	3
15	23	F	169	52	18	3
16	24	M	175	70	23	9
17	34	M	174	84	28	0
18	25	F	170	53	18	0
19	28	M	184	76	22	3
MEAN (Standard deviation)	27 (5)		174 (10)	68 (12)	23 (3)	5.1 (4.9)

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92 Protocol

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94 The experimentations were performed at the Laboratory of Biomechanics and Application of Marseille.
 95 The participants were seated in an Alpha kart with an adjustable seat (Fig. 1) and were asked to
 96 perform three types of physiological motions: axial rotation, lateral bending and flexion-extension.
 97 Three repetitions were performed for each movement. The participants were instructed to perform
 98 these motions at maximum flexibility, but without any discomfort and at their own pace. All
 99 experiments were conducted by two operators.



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Fig. 1 Experimental set-up and measurements; **a** Volunteer's position and posture measurements; **b** Position of physical optoelectronic markers, virtual markers used for range of motion measurement on the helmet and measurements of the anterior and posterior gap

105 First, this series of motions were performed with a helmet (Aero, model E11 050023/P-806428 Model
106 FF311, 1,400 g, size L) and no neck brace and then with six different neck braces: Leatt Moto GPX (500
107 g, size L/XL), Leatt GPX 5.5 (790 g, size L/XL), EVS R4 (635 g, adult size), EVS RC Evolution (1,400 g, adult
108 size), Alpinestars BNS 2 (1,800 g, size L/XL) and Speed Racewear (300 g, adult size) (Fig. 2). Each model
109 was assigned a specific letter code (Fig. 2). The same helmet and neck braces sizes were used for all
110 the volunteers in order to harmonize the test and investigate the influence of fitting. The order of the
111 neck brace tested was randomized.

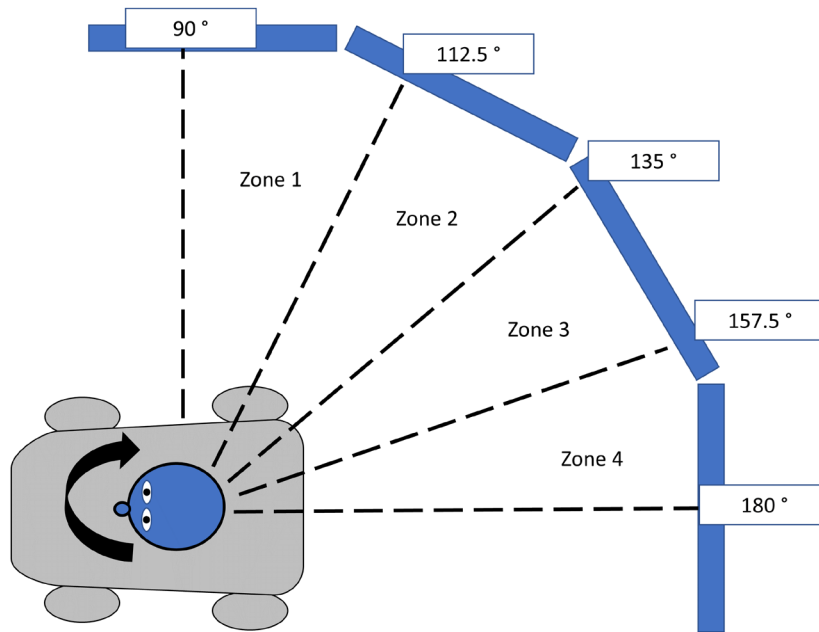
112 The Leatt Moto GPX (model A), Leatt GPX 5.5 (model F), EVS R4 (model B) and Alpinestars BNS 2 (model
113 C) are all composed of a rigid polymer exterior and foam. The Speed Racewear (model D) is composed
114 of foam and fabric only. The EVS RC Evolution (model E) is composed of a polymer material on the
115 sides and in the back, but the neck is surrounded by a foam material. Therefore, the Speed Racewear
116 EVS RC Evolution are categorized as “soft” neck braces. As can be seen in Fig. 2, only the EVS R4 and
117 Speed Racewear are “low-profile,” meaning they do not include an elevated structure to stop posterior
118 motion.

119 The participants were equipped with six optoelectronic markers at the helmet (Fig. 1). The Codamotion
120 (Charnwood Dynamics Ltd.) system was used. The acquisition was performed at 100 Hz. The volunteers
121 were placed at 2.3 m from the Codamotion tower. Before each test, the volunteers were asked to turn
122 their heads to the right and to indicate the last label they could see or read on the panels behind them
123 (Fig. 3) to evaluate their field of view with the different neck braces. This approach was designed in-
124 house to gather preliminary data on the effect of neck braces on the field of view.



125

126 **Fig. 2** Neck braces used in this study; **a** Leatt Moto GPX; **b** EVS R4; **c** Alpinestars BNS Tech-2; **d** Speed Racewear; **e** EVS RC
127 Evolution; **f** Leatt Moto GPX 5.5



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Fig. 3 Field of view assessment using panels behind the kart and the volunteers. The volunteers would designate the last panel that they can see by turning their heads right

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132 **Data analysis**

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134 Sagittal pictures of the participants were taken with each neck brace. The software Kinovea
 135 (<https://www.kinovea.org/>) was used to measure the anterior and posterior gap between the helmet
 136 and each neck brace as recommended by Leatt in their user manual [22] to evaluate the neck brace
 137 fitting (Fig. 1). The posture of each participant was also assessed by measuring the knee, hip and neck
 138 angle, as shown in Fig. 1. The knee angle was measured between the ankle and the knee lateral
 139 epicondyle and following the femur and the tibia. The hip angle was measured between the knee
 140 lateral epicondyle and the acromion, following the line of the femur. The neck angle was measured
 141 between the middle of the ear auditory canal and the acromion following the horizontal line from the
 142 acromion. Each of these measurements was taken three times, and the mean value was used.

143 The motion data analysis was performed with a Matlab script (Matlab R2021b, Mathworks, Natick,
 144 USA). Virtual markers were composed from the physical markers position to represent the occiput, the
 145 crown of the head and the extreme lateral point of the head (Fig. 1). The rotation matrix (R) of these
 146 points was measured throughout the test using the Kabsch algorithm. The ROM was measured from
 147 the rotation matrix using the roll, law, pitch calculation method (Equations 1 to 3) where R is the
 148 rotation matrix and i is the time step.

149 Axial rotation (yaw):

150
$$yaw(i) = \frac{180}{\pi} atan^2(R(2,1,i), R(1,1,i)) \quad (1)$$

151 Flexion-Extension (pitch):

$$152 \quad \text{pitch}(i) = \frac{180}{\pi} \text{atan}^2(\mathbf{R}(3,1,i), \sqrt{(\mathbf{R}(3,2,i))^2 + (\mathbf{R}(3,3,i))^2}) \quad (2)$$

153 Lateral bending (roll)

$$154 \quad \text{roll}(i) = \frac{180}{\pi} \text{atan}^2(\mathbf{R}(3,2,i), \mathbf{R}(3,3,i)) \quad (3)$$

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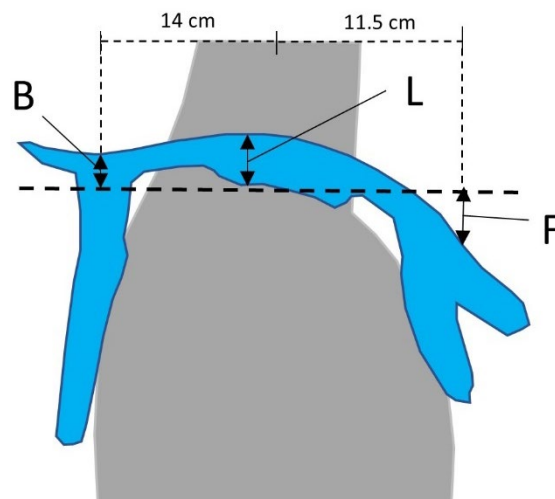
156 Peak values were extracted from the ROM data, and the mean ROM was measured from the three
157 repetitions.

158

159 Neck brace design measurements

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161 The six neck braces used were put on an anthropometric dummy (Faurecia, France) and three
162 measurements were made with a caliper: Back (B), Front (F) and Lateral (L) (Fig. 4). The measurement
163 points were defined by asking a 50th-percentile male wearing a helmet and a neck brace (model F) to
164 move to his maximum lateral bending, flexion and extension. The points of contact between the
165 helmet and the neck brace were marked and the measurements were made at these points to measure
166 the distance between the neck brace and the height of the shoulder (dotted line on Fig. 4). A
167 measurement jig fitted to the torsoform's neck was made to ensure that the measurements were done
168 at the same point for each neck brace. Points B, L, and F were respectively at 14, 13, and 11.5 cm
169 from the center of the dummy's neck.



170

171 **Fig. 4** Neck brace measurements on anthropometric torsoform

172 For each neck brace, the measurements (B, L, F) were plotted in relation to the corresponding ROM
173 measured on the volunteers, for example, lateral bending for the measurement L. Therefore, extension
174 ROM was plotted relative to B, lateral bending ROM relative to L and flexion ROM relative to F. A linear
175 regression was done for each of these relations and the r^2 was extracted to test the strength of the
176 relation. The Pearson correlation coefficients were also measured for these relations. Then, the

177 Pearson correlation coefficient was calculated for the anterior and posterior gaps (Fig. 1) in relation to
178 the flexion ROM and extension ROM, respectively, for each participant.

179

180 Results

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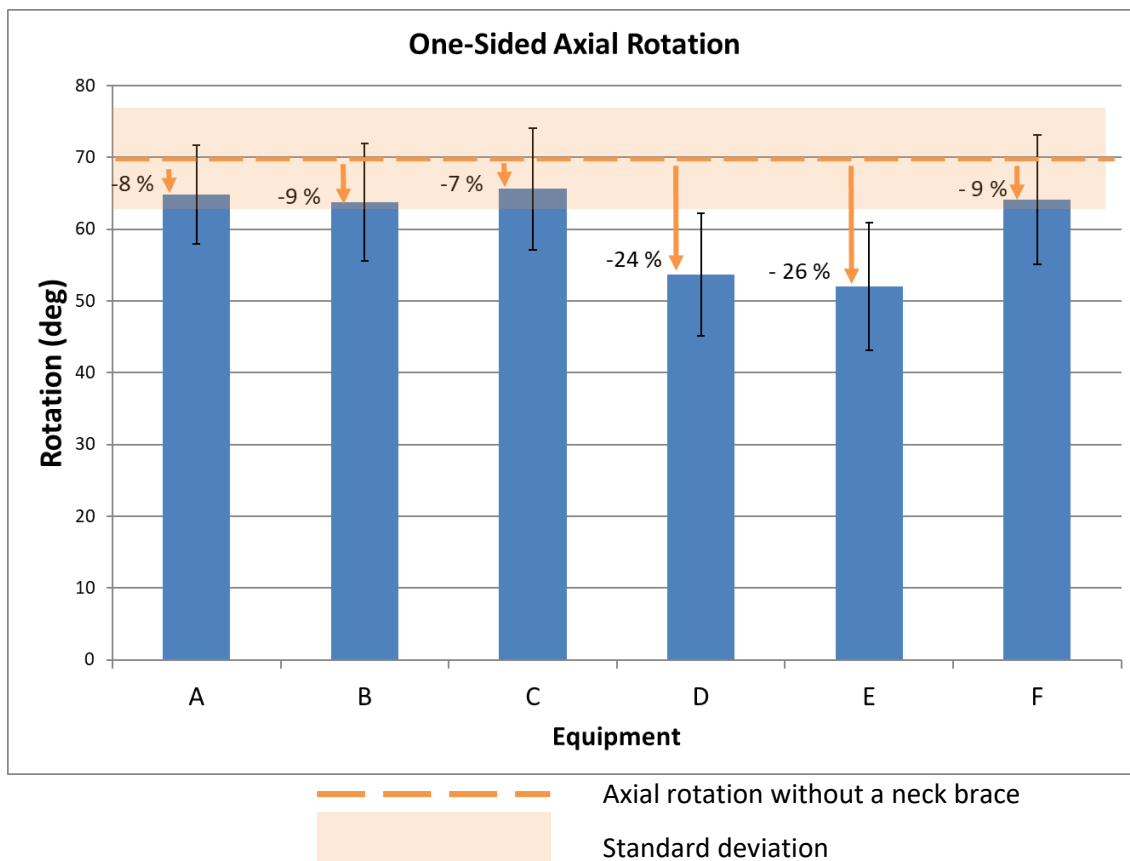
182 Posture

183 The participants' postures were evaluated in the kart. The mean knee, hip, and neck angles were 135°
184 (SD = 9), 110 (SD = 7) and 99° (SD = 7) respectively. The posture was similar between the participants,
185 probably because of the rigidity of the seat. A coefficient of variation of 1 % was obtained for the
186 posture measurements, demonstrating the measure's repeatability.

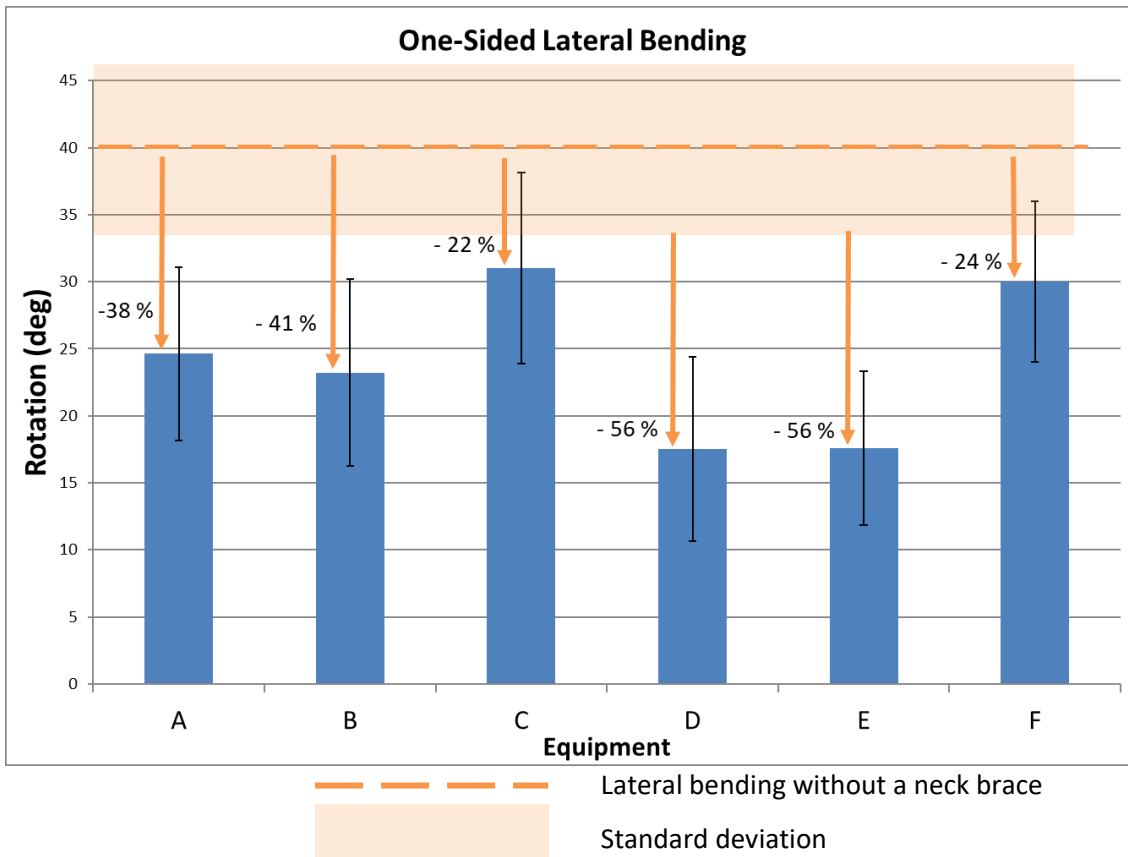
187 Range of motion (ROM)

188 Fig. 5 to Fig. 7 show the difference in ROM for each neck brace relative to the ROM with the helmet
189 only for axial rotation, lateral bending, flexion, and extension. In general, flexion-extension was the
190 most efficiently reduced motion, and axial rotation was the least restricted direction by the neck
191 braces.

192

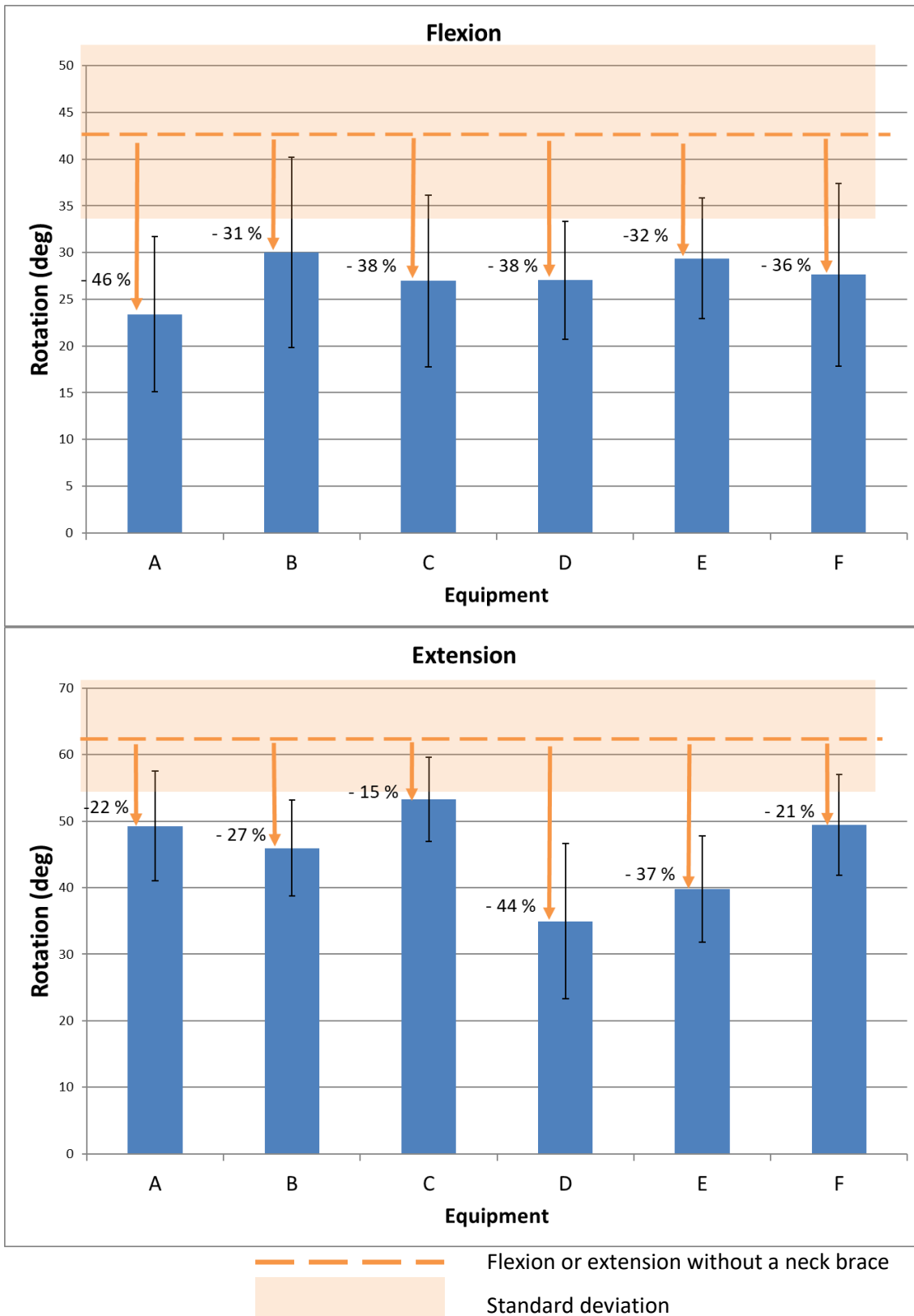


193 **Fig. 5** One-sided axial rotation with each neck brace. The error bars show the standard deviation. The difference in
194 percentage compared to no neck brace is noted above the results. The dotted orange line represents the axial rotation with
195 only a motorcycle helmet and no neck brace. A = Leatt Moto GPX, B = EVS R4, C = Alpinestars BNS Tech-2, D = Speed
196 Racewear, E = EVS RC Evolution, F = Leatt GPX 5.5



197 **Fig. 6** One-sided lateral bending difference relative to no neck brace. The error bars show the standard deviation. The
 198 difference in percentage compared to no neck brace is noted above the results. The dotted orange line represents the
 199 lateral bending with only a motorcycle helmet and no neck brace. A = Leatt Moto GPX, B = EVS R4, C = Alpinestars BNS
 200 Tech-2, D = Speed Racewear, E = EVS RC Evolution, F = Leatt GPX 5.5

201



202 **Fig. 7** Flexion-extension difference relative to no neck brace. The difference in percentage is noted above the results. The
 203 error bars show the standard deviation. The difference in percentage compared to no neck brace is noted above the results.
 204 The dotted orange line represents the extension with only a motorcycle helmet and no neck brace. A = Leatt Moto GPX, B =
 205 EVS R4, C = Alpinestars BNS Tech-2, D = Speed Racewear, E = EVS RC Evolution, F = Leatt GPX 5.5

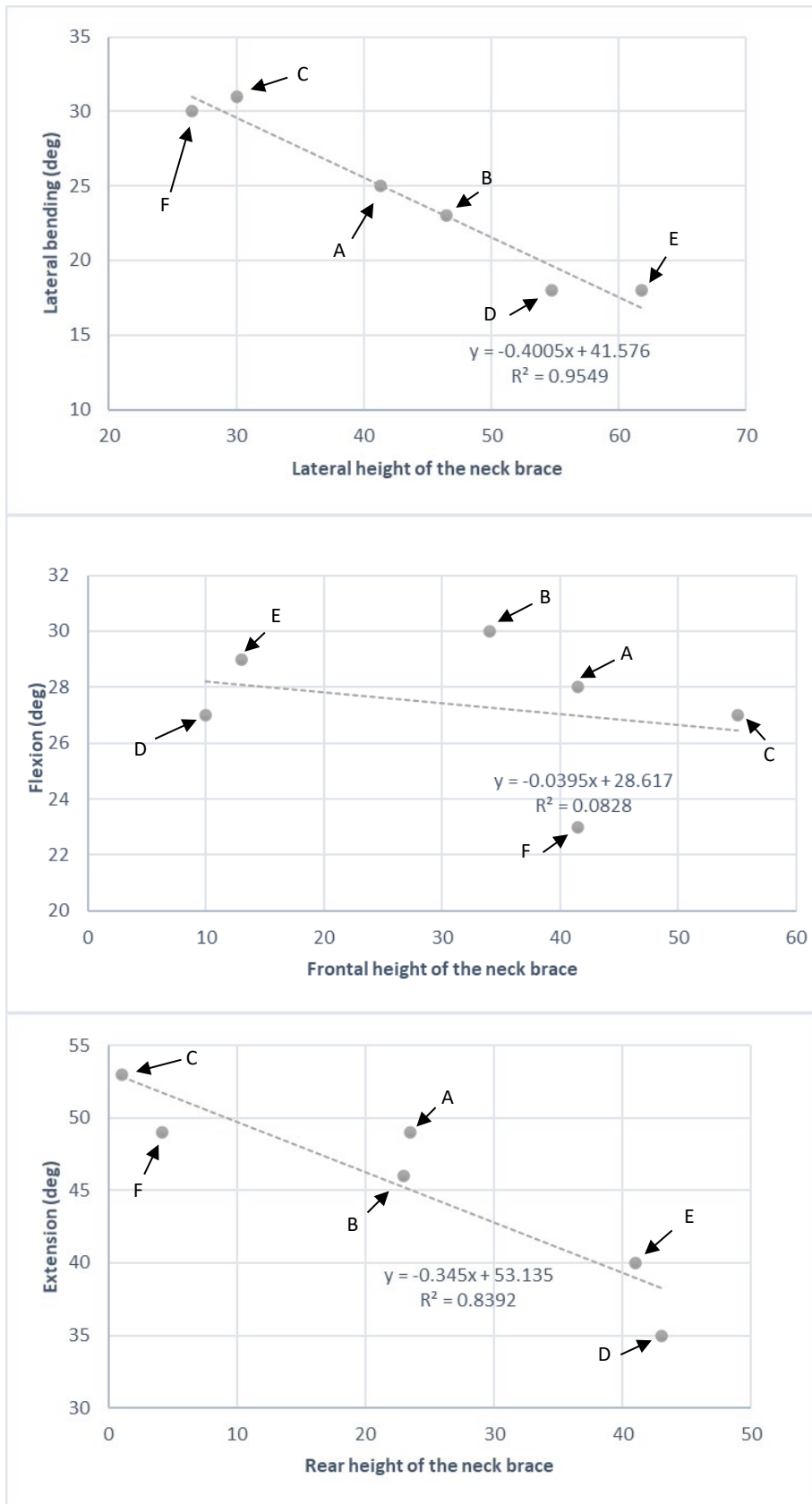
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207 **Field of view**

208 As assessed on the panels (Fig. 3), the participants' mean field of view was zone 3 (157.5°) without
209 equipment. Wearing a helmet did not reduce the field of view. With the neck braces, only the soft neck
210 braces (models D and E) reduced the field of view to zone 2 (135°). The rigid neck braces did not affect
211 the field of view.

212 **Neck brace design and mobility**

213 Fig. 8 shows the linear relation between the mean head ROM and the neck brace measurements (L, B
214 and F). A r^2 of 0.84 and 0.95 was found for extension ROM in relation to measurement B and for lateral
215 bending ROM with measurement L, respectively, showing a strong correlation between these ROM
216 and the neck brace design features. However, the relation between flexion and measurement F gave
217 a r^2 of 0.08, showing no correlation.



219
220

Fig. 8 Relations between range of motion and measurements of the neck brace made on the torsoform. A = Leatt Moto GPX, B = EVS R4, C = Alpinestars BNS Tech-2, D = Speed Racewear, E = EVS RC Evolution, F = Leatt GPX 5.5

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222 The Pearson correlation coefficients were 0.997 between the neck brace lateral measurement (L) and
223 the mean lateral bending, 0.96 between the posterior measurement (B) and extension and 0.29
224 between the anterior measurement (F) and flexion. All p-values were under 0.05.

225 **Neck brace fitting and mobility**

226 The mean anterior and posterior gap between the helmet and the neck brace for each neck brace is
227 shown in Table 2. Model B was the neck brace with the biggest anterior gap (5.6 cm), and model C
228 was the one with the biggest posterior gap (9.5 cm). Model D was the neck brace with the smallest
229 anterior and posterior gap: 0.9 and 0.3 cm, respectively.

230

231 **Table 2 - Anterior and posterior gap between the helmet and the neck brace and Pearson correlation coefficient (r)**
232 **between the anterior and posterior gap and flexion-extension range of motion.**

Neck brace	Anterior gap [cm]		Pearson correlation coefficient between anterior gap and flexion		Posterior gap [cm]		Pearson correlation coefficient between the posterior gap and extension range of motion	
	Mean (SD)		r	p-value	Mean (SD)		r	p-value
Model A	3.6 (2.2)		0.81	9.7E-06	8.6 (1.5)		0.57	3.1E-03
Model B	5.6 (2.5)		0.74	5.6E-05	8.0 (1.4)		0.30	3.5E-02
Model C	4.1 (2.6)		0.53	3.1E-03	9.5 (1.5)		0.54	3.1E-03
Model D	0.9 (1.2)		0.28	3.5E-02	0.3 (0.6)		0.32	3.5E-02
Model E	4.3 (2.3)		0.58	3.7E-04	4.5 (1.8)		0.57	3.1E-03
Model F	5.2 (3.0)		0.87	4.0E-07	9.1 (1.7)		0.80	9.7E-06
All neck braces combined	-		0.61	3.7E-04	-		0.70	5.6E-05

233

234 The Pearson correlation between the gaps measured for each participant and the measured flexion or
235 extension is also reported (Table 2). When incorporating the results for all the neck braces, the Pearson
236 correlation coefficient was 0.61 for flexion and 0.70 for extension. All p values showed statistical
237 significance.

238

239 **Discussion**

240

241 The hypothesis that physiological head ROM restrictions are linked with neck brace fitting and design
242 was confirmed by performing experimental tests on twenty volunteers with six different neck braces.
243 Indeed, the chosen design parameters were well correlated with extension and lateral bending with r^2
244 of 0.84 and 0.95, respectively. Plus, the Pearson correlations between anterior or posterior helmet-

245 neck-brace gap and flexion or extension were measured at 0.61 and 0.70, respectively. This is the first
246 study to measure head ROM in a kart and to assess the field of view with different neck braces. It is
247 also the first study to examine correlations between neck brace design and head ROM.

248 The mean helmeted head ROM without a neck brace measured in this study (43° in flexion, 63° in
249 extension, 140° in axial rotation and 80° in lateral bending) was similar to the mean ROM measured by
250 Lecoublet et al. [17] for volunteers seated in a chair (48.5° in flexion, 53° in extension, 125° in axial
251 rotation and 79° in lateral bending). Lecoublet et al. [18] reported a significant difference between the
252 head ROM in axial rotation on a scooter (153°) or a racing motorbike (135°). The results of this study
253 (140°) were situated close to the mean of these reported values.

254 All the neck brace models reduced the head ROM as expected and as seen in previous studies [16, 18].
255 Only Gorasso et Petrone [15] reported a slight increase (1 %) in axial rotation with a neck brace, but
256 they did not specify which neck brace model was used. None of these studies investigated the effect
257 of neck brace design. As Lecoublet et al. (2021) observed, flexion-extension was the most efficiently
258 reduced motion. This was expected since the manufacturers have historically designed their products
259 to reduce motion in the sagittal plane [5, 9]. In general, axial rotation was the least restricted direction
260 by the neck braces, decreasing by 7 to 26 %. The "soft" neck braces, made completely or partially with
261 foam, models D and E, were the most restrictive devices in all directions except flexion. They were the
262 only ones to reduce the field of view, though only by one zone (22.5°). Low-profile neck braces like
263 model B and model C were generally less effective in reducing physiological mobility.

264 Considering the neck brace fitting, the anterior and posterior gaps presented a high standard deviation,
265 demonstrating the inter-individual morphological differences. The soft neck braces had the smallest
266 gap between the neck brace and helmet, and the correlations between the gaps and the flexion or
267 extension ROM were poorer with model D, which is not surprising since it is a soft collar and its position
268 was not fixed, therefore it moved with the head. Considering all types of neck braces, there was a
269 significant correlation between the gaps and the ROM (0.61 in flexion and 0.70 in extension).
270 Manufacturers' fitting recommendations are usually limited to chest size or mass, which seems
271 insufficient for karting drivers or motorcyclists to make a proper decision when choosing a neck brace.
272 The results of this study support using the gap between the helmet and the neck brace measured on
273 a driver to give recommendations on the choice of neck brace or the choice of size.

274 The current study's results showed that a given neck brace design can be simply correlated with the
275 allowed ROM in lateral bending and extension using an anthropometric dummy. This is useful since it
276 is a quick and economical solution to evaluate neck brace designs. However, no correlation was
277 reported in flexion. This may be due to the complexity of the flexion motion, which can be decomposed
278 between pure rotation and anterior translation. Also, the evaluated neck brace designs were different
279 in the anterior part, for example, model B left 5.6 cm in anterior between the helmet and neck brace.
280 In contrast, others were closer to the neck, for example, model D left 0.9 cm and 0.3 cm between the
281 neck brace and the helmet in anterior and posterior, respectively.

282 While the link between neck brace fitting, neck brace design, and physiological ROM discussed in this
283 paper is novel and important to improve the design of neck braces, it must be stated that head and
284 neck response as a result of interaction with a neck brace during a traumatic condition is unknown.
285 Notably, Khosroshahi et al. [10] observed, using numerical simulation, that a neck brace can generate
286 higher loads in the cervical spine and increase the stress in the vertebrae at certain spinal levels. Nasim

287 [9] also observed that neck braces could increase the cervical spine compressive or shear force in
288 different injury simulations. De Jongh et al [6] showed that a neck brace model reduced upper neck
289 flexion moment, but increased the axial tension for near vertex impacts reproduced on a Hybrid III
290 dummy. Finally, even though the results showed that soft collars were the most restrictive, Sun et al.
291 [8], in a finite element study, reported that a soft neck brace was inefficient in protecting the cervical
292 spine in a traumatic situation. Further studies, combining the characterization of the allowed
293 physiological ROM and the biomechanical neck response using numerical simulation are needed.
294 Experimental testing should also be performed to characterize the mechanical behaviour of different
295 neck braces under high-velocity impacts, similarly to the methodologies proposed in de Jongh et al. [6]
296 and de Jongh et al. [7].

297 Considering the other limitations of this study, maintaining the field of view is important for drivers'
298 comfort and safety and was reported for the first time here with different neck brace models. As a first
299 approach, panels and zones were used to measure the field of view without using a previously
300 established protocol. It would be possible to use eye-tracking technology to have a more precise
301 measurement of the field of view. Future studies could focus on the impact of the field of view
302 restriction on the risk of accidents. Only one helmet size and one brace size were used for each brand.
303 Therefore, some volunteers wore a neck brace too small or too big for them which could have affected
304 their comfort and changed their mobility, but this choice highlighted the influence of sizing on head
305 ROM. Also, only one type of helmet was used, but since the interaction between the helmet and neck
306 brace is essential in the ROM restriction, other helmets could lead to different results.

307 In this study, an anthropometric dummy was used to measure neck brace design parameters in a
308 standardize manner, but these measurements and their influence could vary from one driver to
309 another depending on morphological differences. Furthermore, this study included only twenty
310 volunteers, and it would be interesting to gather more results, considering the high inter-individual
311 variability observed, and to obtain results from younger volunteers since many karting drivers are
312 teenagers. Future works should also investigate the influence of other anthropometric parameters in
313 addition to helmet-neck brace gap, for example head and neck circumferences, on neck brace fitting
314 and head mobility. Finally, enhanced anthropometric test dummies need to be constructed to test the
315 efficacy of novel neck braces while considering bio-fidelity in head and neck motion and individual
316 morphological differences

317

318 **Conclusion**

319

320 The results showed that all tested neck braces reduced head ROM. The rigid neck braces did not restrict
321 the field of view. A simple, but effective method using an anthropometric dummy to correlate the head
322 ROM in lateral bending and extension with neck brace design parameters was proposed. The
323 recommendations for sizing are usually limited to the chest size and mass only, which may not ensure
324 optimal comfort and head mobility restriction. The results of this study show that the gap between the
325 helmet and the neck brace influences head mobility and, therefore, could be considered when
326 selecting the appropriate neck brace size and brand.

327

328 **Acknowledgments**

329 This study was funded by Gustave Eiffel University.

330

331 **Statements and Declarations**

332 The authors have no competing interests to declare. The raw dataset is unavailable since its diffusion
333 outside the research team was not presented to the ethical committee.

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