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RESEARCH ARTICLE

Carbon Racing Wheelchair Frames: Trespassing Technological Unfairness?

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ABSTRACT

This study aimed to compare the performance at World Marathon Majors of three types of racing wheelchair frame materials: Aluminum (Alu), mixed Carbon-Aluminum (CA), and carbon (Carb). Three elite wheelchair athletes (wheelers) (1 male and 2 females) were chosen for the performance analysis, which was conducted on 117 marathons (Alu, n = 49; AC, n = 25; Carb, n = 43). Compared to Alu and CA, Carb was significantly faster (249.18 ± 168.39 s or 4.07%; p = 0.001; Effect size = 0.89) and (388.60 ± 224.06 s or 6.34%; p = 0.0001; Effect size = 0.93), respectively. In addition, no interactions were observed (p > 0.05) between the material of the frame and i) the course profile, ii) the steadiness of intensity, iii) the elevation gained from the start to the finish line, and iv) the surface quality. However, Carb frames behavior in Majors, in which there are remarkable descent sections were 6.9% faster or 412.4 s (effect size = 0.64) relative to Alu, showing an even greater advantage with CA (7.6% or 455.4 s; effect size = 0.63). In conclusion and considering the remarkable advantage in terms of performance that Carb frames confer to elite-wheelers compared to those who use Alu and CA frames, as also the unaffordable price of Carb racing wheelchairs for most elite-wheelers, we advocate for consideration of strict regulations (i.e., do not allow the use of Carb frames at sanctioned marathons) by the government body of this sport IPC Athletics.

Keywords: Biomechanics, marathon, racing wheelchair, technological doping.

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1. Introduction

World Marathon Majors is a championship-style competition for marathon runners and wheelchair athletes (wheelers), which comprises the six greatest marathons on the planet and is governed by World Athletics rules. In this regard, three Majors are held in spring (Tokyo, Boston, and London), while in fall, they are celebrated in Berlin, Chicago, and New York City. Interestingly, wheelers have become more and more popular over the years and, as in the elite-runners field, the elite-wheelchair division offers in each one of the Majors significant prize money awards (i.e., up to 55,000 $ for both male and female winners, plus up to 50,000 $ in the case of a new course record, decreasing prizes until top ten finishers). In addition, there is the Major Series, a league where in each one of the six events, wheelers can score points, depending on their finishing position (first place 25 points, second 16 points, third 9 points, fourth 4 points, and fifth 1 point). The greatest score from the best 4 Majors (5 in the Paralympic Games or World Championships years) is considered for final ranking. Interestingly, last year, Majors equalized prize money to series champions for runners and wheelers, so Majors champions in the elite-running and elite-wheelchair field won 50,000 $ in each gender, being the prize pool (first place 50000 $, second place 25,000 $, third place 12,500 $, fourth place 7,500 $, and fifth place 5,000 $). More details can be found at Abbott World Marathon Majors website.

On the other hand, the mechanical stress that wheelchair racing imposes on those athletes (i.e., the impact in each pushing phase of the stroke) is lower compared to the one suffered by runners, which is one to three times body weight in each ground contact (Nigg & Wakeling, 2001) due to body mass is supported by an aluminum or carbon cage (Brizuela Costa *et al*., 2009). Thus, most of the elite wheelers take part in the entire Majors circuit, even in week-to-week events (e.g., Boston and London) or even in day-to-day events (Chicago and Boston Marathons were held in 2021 due to the COVID-19 era within 24 hours difference, taking part in both events top wheelers). In this regard, last year (2023), the wheelchair male Majors Series winner won the six Majors.

Conversely, three main types of frames are used by wheelers: i) aluminum (Alu), ii) mixed carbon-aluminum frame (CA), and iii) carbon frame (Carb) (Fig. 1). In addition, a standard frame of 1.88 m in length with carbon disc wheels will weigh ∼9 kg (Alu), ∼9.7 kg (CA), and ∼8 kg (Carb). The prizes for those types of frames with carbon disc wheels or similar wheels oscillate between 5000–9000 $ (Alu), 12000–14000 $ (CA), and 30000–45000 $ (Carb). Furthermore, differences in the construction design of three types of frames exist, as Carb is built in a unique piece without welding parts, which characterizes the Alu frame. In this line, the CA frame has an aluminum cage that cannot be welded to the main carbon bar, thus making it weaker as more energy might be dissipated.

Interestingly, as in bicycle design and construction, where the major objective is the material selection with the least amount of mass (on the same level of strength), Carbon fiber Reinforced Plastics (CFRP) is the most suitable material even though the cost is higher, compared with Aluminum alloys (Syed & Marrapu, 2022). In addition, some Carb models might be assessed in the wind tunnel, which can decrease the aerodynamic drag throughout the optimal athlete's position (García-López *et al*., 2008). However, not all elite wheelers can benefit from this type of test due to its expense (see Fig. 2).

Regarding regulation of this sport, IPC-Athletics (main government body) states that wheelers can use any type of frame if this has been in the market for ≥1 year. On to this line, World Athletics states that carbon shoes used for racing cannot be prototypes (i.e., a racing frame that costs ∼30,000 $ is unavailable for the vast majority of elite wheelers, thus sort of a prototype), and its design needs to be accomplished for being considered as legal shoes (e.g., Kipchoge's shoes of the Breaking 2 record in Vienna) were by that time illegal and could not be used in any World Athletics sanctioned event as any Major (World Athletics, 2024).

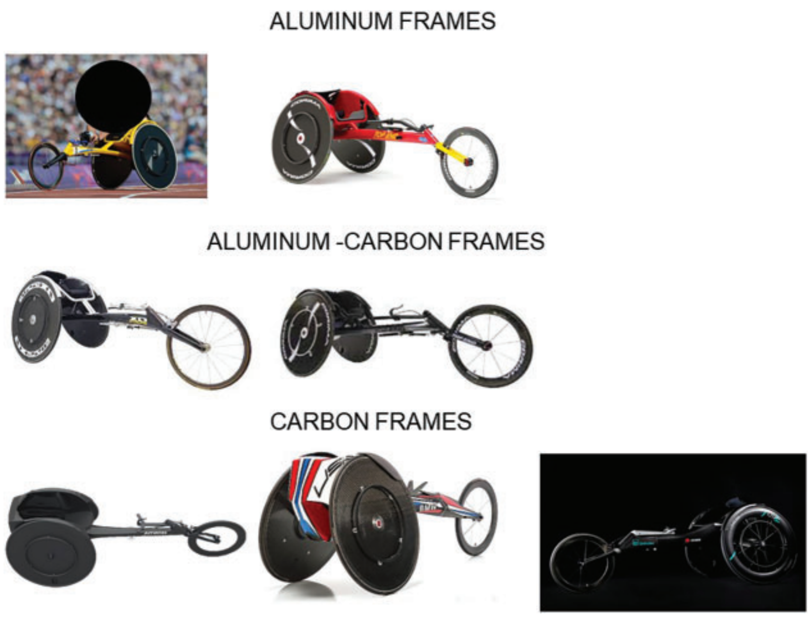

Fig. 1. Type of racing wheelchair frames.

Fig. 2. Carbon frame being tested at the wind tunnel.

Recently, the Kenyan female athlete Helen Obiri was disqualified from the Istanbul Half Marathon in the 2021 edition because she ran under prototype shoes. What is clear is that a top legal carbon shoe can be afforded by the vast majority of elite runners, but this circumstance won't be given in the elite wheelchair field (∼250 $ vs. ≥ 30,000 $), a fact which is aggravated in developing countries (i.e., equity is sport is not respected among all participants).

On other matters, technological doping has been defined as using advances in technology, which include devices, materials, and other products external to the body to increase human performance (Savulescu, 2017). We might argue that, to preserve the level play of the field, not only biological but also technological doping could be considered as part of the regulation in any sport.

Considering all the above mentioned, the aim of this pilot study was to analyze whether Carb frames significantly improve performance in marathons versus Alu and CA wheelchair models to support our hypothesis of unfairness and the need for new regulation to balance the play of field.

2. Materials and Methods

In order to analyze the efficiency of the three types of racing wheelchair frames, there were chosen three Majors Series dominants athletes from the last decade and a total of 117 Majors marathons were included in the statistical analysis until the New York City Marathon 2022, held on November 6th, 2022. To consider, we categorized each Major performance time with the type of frame used (Alu, CA, or Carb). This study is exempt from ethical approval because it is not an intervention research conducted with humans.

2.1. Data Search

Data was obtained from Majors website or each Major marathon website results section.

2.2. Participants

The first participant studied was the Swiss athlete Marcel Hug (36 years old), who had won until November 7th, 2022 (data limit time frame) 27 Majors out of 41 (65.9% chance to win a Major) during his career since his first Major participation (Berlin Marathon 2011 edition). In addition, he won Majors Series X, XI, XIII, and XIV.

The second participant studied was the Swiss athlete Manuela Schär (38 years old), who had won until data limit time frame 20 Majors out of 38 (52.6% chance to win a Major) during her career since her first Major participation (Berlin Marathon 2013 edition). Moreover, she won Majors Series XI, XII, and XIII.

The third participant studied was the American athlete Sussanah Scaroni (31 years old), who had won until data limit time frame 2 Majors out of 38 (5.3% chance to win a Major) during her career since her first Major participation (Chicago Marathon 2011 edition). Moreover, she won the last Majors Series (XIV).

2.3. Majors Sample with Each Type of Frame

Alu, n = 49; AC, n = 25; Carb, n = 43.

2.4. Interaction Factors

On the other hand, we requested three pro-wheelers (HG, DR, MS) to define different factors that should be considered to analyze the interaction between the type of frame used and the following mentioned factors:

2.4.1. Course Profile

1. Flat courses were considered in Berlin, Chicago, London, and Tokyo.
2. Hilly courses were considered in Boston and New York City.

2.4.2. Steadiness of Intensity

1. Steady efforts were considered in Berlin, Chicago, London, and Tokyo.
2. Non-steady efforts were considered in Boston and New York City.

2.4.3. Decrease in Elevation

"The overall decrease in elevation between the start and finish shall not exceed 1:1000, i.e., 1 m per km (0.1%)." (World Athletics, 2024).

1. Decrease in elevation > 1:1000 was in Boston.

2. Decrease in elevation < 1:1000 were in Berlin, Chicago, London, New York City, and Tokyo.

2.4.4. Surface Quality

1. Smooth surfaces were in Berlin, Boston, and Tokyo.
2. Rough/bumpy surfaces were in Chicago, London, and New York City.

2.5. Statistical Analyses

All data are presented as mean (±SD). Data were screened for normality of distribution with a Kolmogorov-Smirnov test. A repeated measures multifactorial ANOVA was carried out for variable TIME including factor MATERIAL with levels Alu, CA, and Carb; factor COURSE PROFILE with levels flat and hilly; factor STEADINESS of INTENSITY with levels steady and non-steady; factor DECREASE IN ELEVATION with levels >42.195 meters and ≤42.195 meters; factor SURFACE QUALITY with levels smooth and rough/bumpy, being dependent variable the TIME (s). A post hoc LSD multiple range test was performed to examine differences between the levels of the factor. Effect size associated with change in performance with Alu, CA, and Carb were calculated using Cohen's d (difference in mean scores over time divided by pooled SD) and were interpreted as trivial ($d \leq 0.19$), small (0.20–0.49), medium (0.50–0.79), and large ($d \geq 0.80$) (Hopkins *et al.*, 2009). The alpha level of 0.05 was stated for the level of statistical significance. Statistical analyses were performed using the Statgraphics version 16.1.17 software (STSC, Inc., Rockville, MD, USA).

3. Results

The performance at the Majors was greater ($p = 0.0010$) with Carb, compared to both Alu and CA (see Table I for mean values, standard error with 95% Confidence Intervals (CI), and effects size). In fact, Carb was significantly faster relative to both Alu (249.18 ± 168.39 s) and CA (388.60 ± 224.06 s). However, no differences were observed ($p > 0.05$) between Alu and CA. Means and 95% CI of times with 3 types of frames are plotted in Fig. 3.

3.1. Material and Course Profile and Material and Steadiness of Intensity Interactions

The same Majors conform to both types of interactions. Thus, both interactions are discussed together. In addition, no interactions were found ($p = 0.9955$). Moreover, non-significantly ($p = 0.5713$) faster times were found in flat and non-steady effort Majors, relative to hilly and steady effort Majors (6019.59 ± 79.94 vs. 6098.92 ± 115.26; ES = −0.37). See Tables II and III for mean values, standard error with 95% Confidence Intervals (CI), and effects size (ES).

TABLE I: Marathon Performance with Different Types of Racing Wheelchair Frames

Material	Mean ± (SD) (s)	Lower limit (s)	Upper limit (s)	Effect size Alu-CA	Effect size CA-Carb	Effect size Alu-Carb
Alu	6126.10 ± 58.90†*	6045.40	6278.80	−0.67	0.93	0.89
CA	6301.52 ± 90.68†*	6121.85	6481.19			
Carb	5912.92 ± 62.54	5789.00	6036.83			

Note: †Differences from Carb; *Level of significance ($p = 0.001$).

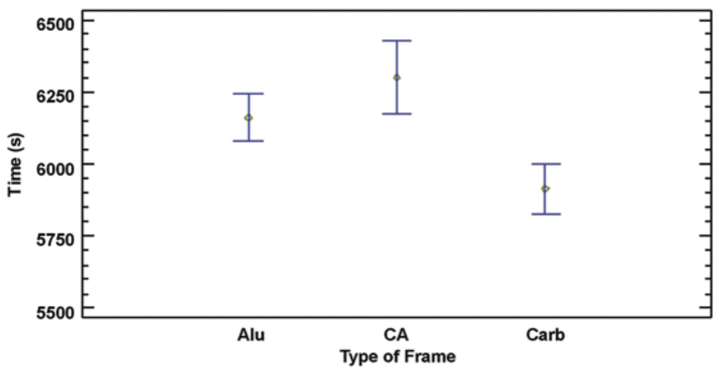

Fig. 3. Type of frame's times at the Majors. Alu, aluminum; CA, carbon-aluminum; Carb, carbon; A difference was observed between Carb and Alu ($p = 0.0010$) and Carb and CA ($p = 0.0010$).

TABLE II: Material by Course Profile Interactions

Material by course profile interaction	Mean ± SD (s)	Lower limit (s)	Upper limit (s)
Alu, Flat (1)	6248.48 ± 117.04	6016.56	6480.41
Alu, Hilly (2)	6328.50 ± 168.08	5995.43	6661.57
CA, Flat (3)	5856.19 ± 168.08	5523.12	6189.26
CA, Hilly (4)	5917.89 ± 224.11	5473.80	6361.98
Carb, Flat (5)	5954.09 ± 118.85	5718.58	6189.61
Carb, Hilly (6)	6050.36 ± 202.72	5648.67	6452.06
ES 1-2		−0.26	
ES 3-4		−0.15	
ES 5-6		−0.28	
ES 1-3		0.80	
ES 2-4		0.72	
ES 3-5		−0.32	
ES 4-6		−0.30	
ES 1-5		0.78	
ES 2-6		0.60	

Note: (#): Number of interactions; ES: Effect size.

TABLE III: Material by the Steadiness of Intensity Interactions

Material by steadiness of intensity interaction	Mean ± SD (s)	Lower limit (s)	Upper limit (s)
Alu, Steady (1)	6248.48 ± 117.04	6016.56	6480.41
Alu, Non-steady (2)	6328.50 ± 168.08	5995.43	6661.57
CA, Steady (3)	5856.19 ± 168.08	5523.12	6189.26
CA, Non-steady (4)	5917.89 ± 224.11	5473.80	6361.98
Carb, Steady (5)	5954.09 ± 118.85	5718.58	6189.61
Carb, Non-steady (6)	6050.36 ± 202.72	5648.67	6452.06
ES 1-2		−0.26	
ES 3-4		−0.15	
ES 5-6		−0.28	
ES 1-3		0.80	
ES 2-4		0.72	
ES 3-5		−0.32	
ES 4-6		−0.30	
ES 1-5		0.78	
ES 2-6		0.60	

Note: (#): Number of interactions; ES: Effect size.

3.2. *Material and Decrease in Elevation Interaction*

No interaction between the frame type and elevation decrease was observed ($p = 0.279$). The Boston Marathon, with >42.195 meters decrease in elevation from the start line to the finish line, was non-significantly faster ($p = 0.6210$) compared to the rest of the Majors (5975.27 ± 151.17 s vs. 6052.88 ± 70.91 s; ES = −0.31). See Fig. 4 to observe how Carb frames tend to perform faster in a slightly descending elevation profile at the Boston Marathon than Alu and CA. However, the rest of Majors, CA (the heavier frame) showed a slightly faster behavior compared to Carb and faster than Alu. See Table IV for mean values, standard error with 95% Confidence Intervals (CI), and effects size (ES).

3.3. *Material and Surface Quality Interaction*

While no interaction between the type of frame and the surface quality was found ($p = 0.4824$), there were observed differences between the type of surface Majors ($p = 0.0147$) (see Fig. 5), being the times in smooth surfaces faster compared to rough/bumpy Majors (5853.36 ± 97.88 s vs. 6169.11 ± 81.47 s; ES = −0.87). See Table V for mean values, standard error with 95% Confidence Intervals (CI), and effects size (ES).

4. Discussion

It is noteworthy that the main finding of this study was the significantly ($p = 0.0010$) faster times set with the carbon racing wheelchair frames compared to either Aluminum frames (+249.18 s or

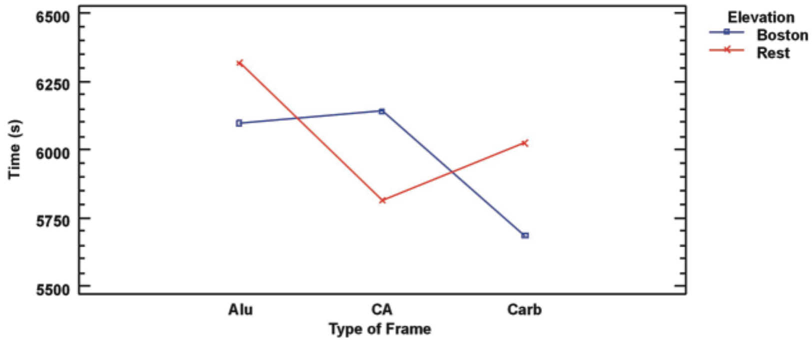

Fig. 4. Interaction of the type of frames and times at Majors with different elevations gained. Blue continuous line representing Boston Marathon (>42.195 m decrease in elevation); red continuous line representing the rest of Majors (≤42.195 m decrease in elevation).

TABLE IV: Material by a Decrease in Elevation Interactions

Material by decrease in elevation interaction	Mean ± SD (s)	Lower limit (s)	Upper limit (s)
Alu, >42.195 m (1)	6098.40 ± 209.94	5682.39	6514.41
Alu, ≤ 42.195 m (2)	6319.79 ± 106.31	6109.14	6530.45
CA, >42.195 m (3)	6141.40 ± 296.90	5553.10	6729.73
CA, ≤ 42.195 m (4)	5812.65 ± 148.45	5518.49	6106.81
Carb, >42.195 m (5)	5686.00 ± 271.03	5148.93	6223.10
Carb, ≤ 42.195 m (6)	6026.19 ± 109.14	5809.92	6246.46
ES 1-2		−0.55	
ES 3-4		0.57	
ES 5-6		−0.64	
ES 1-3		−0.08	
ES 2-4		0.89	
ES 3-5		0.63	
ES 4-6		−0.63	
ES 1-5		0.64	
ES 2-6		0.80	

Note: (#): Number of interactions; ES: Effect size.

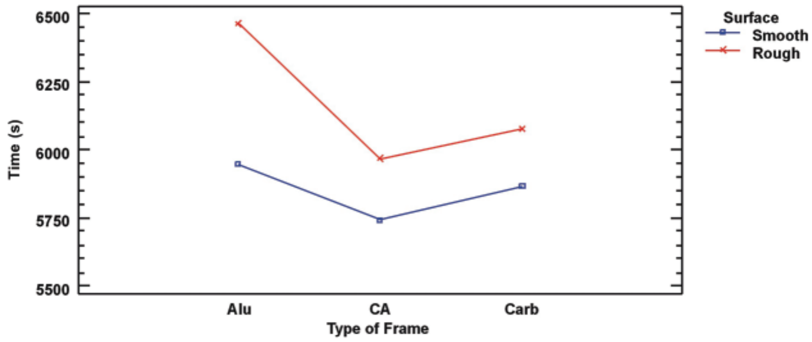

Fig. 5. Interaction of the type of frames and the quality of the Majors surface. Blue continuous line representing smooth Majors surfaces (Berlin, Boston, and Tokyo Marathons); red continuous line representing rough/bumpy Majors surfaces (Chicago, London, and New York City Marathons). A significant level of interaction was found between smooth and rough/bumpy Majors ($p = 0.0147$).

4.07% slower) as also to carbon-aluminum frames (+388.60 s or 6.34% slower). The differences are also supported by the large effect size observed from Alu to Carb (ES = 0.89) and CA to Carb (ES = 0.93), while no differences ($p > 0.05$) were observed when comparing Alu with CA frames (Table I). This might be partly explained by the lighter weight of Carb frames (∼1 kg lighter than Alu and ∼2 kg lighter than CA) due to less force required to accelerate (e.g., speed/pace changes) as also going uphill. Chairs weighing more performed slower in the overall 117 Majors analyzed (CA was 2.9% over the mean, Alu was 0.60% over the mean, and Carb was 3.47% below the mean). In this regard, we found similarities with racing athletics shoes when comparing models with embedded carbon fiber plate that increases longitudinal bending stiffness (Hoogkamer *et al.*, 2018) to minimalist racing flat shoes and heavier highly-cushioned shoe models (i.e., 313 ± 44 g mass), reporting better performance with carbon plate shoes compared to both, racing flat (1.8% slower; $p = 0.032$) and cushioned shoes (2.4% slower; p

TABLE V: Material by Surface Quality Interactions

Material by surface quality interaction	Mean ± SD (s)	Lower limit (s)	Upper limit (s)
Alu, Smooth (1)	5948.83 ± 152.65	5646.34	6251.33
Alu, Rough (2)	6463.77 ± 116.32	6233.27	6694.27
CA, Smooth (3)	5743.50 ± 204.81	5337.66	6149.34
CA, Rough (4)	5968.33 ± 167.22	5636.97	6299.70
Carb, Smooth (5)	5867.75 ± 144.82	5580.78	6154.72
Carb, Rough (6)	6075.22 ± 135.05	5807.62	6342.82
ES 1-2		−0.88	
ES 3-4		−0.30	
ES 5-6		−0.60	
ES 1-3		0.49	
ES 2-4		0.86	
ES 3-5		−0.33	
ES 4-6		−0.33	
ES 1-5		0.26	
ES 2-6		0.83	

Note: (#): Number of interactions; ES: Effect size.

= 0.005) (Hébert-Losier *et al*., 2022). Overall, these differences in performance peaked with the INEOS 1:59 Challenge, when Eliud Kipchoge broke the 2 hours marathon barrier, wearing not commercially available Nike Alphafly prototype shoes. This stunning running performance generated quite a controversy among the sports and scientific community, questioning whether new shoe technology could be in breach of the "spirit" of the sport. Some authors stated that the Nike Vaporfly/Alphafly pushes the perceived acceptability of running shoes to the limits of sports regulations (Dyer, 2020). These perceptions of potential unfairness led consequently to scientific proposals that claim to regulate footwear in road running (Burns & Tam, 2020), which eventually forced World Athletics to introduce a new set of rules (World Athletics, 2024). The differences in performance between different types of shoes resulted in a lower magnitude than the differences we observed in our comparative study between different types of racing wheelchairs (1.8%–2.4% vs. 4.1%–6.7%). If we estimate the differences between the former world record holder in the open men's wheelchair marathon (Heinz Frei, 4814 s) set in the Oita International Wheelchair Marathon in 1999 with an Alu frame and the current world record holder (Marcel Hug, 4667 s) set at the same scenario in 2022 with a Carb frame, we estimate a 3.05% difference, not reaching the 4.07% which we observed in the 117 Majors analyzed in our study, what might lead us to speculate that the current world record would not have been set with the same frame conditions as remain 49 seconds to reach that modeling value (4618 s should be considered a new world record if attending to our data).

On the other hand, it was observed (besides no interaction between the type of material and Majors's surface $p = 0.4824$) that smooth Majors surfaces positively affected finish times by 5.12% (6169.11 ± 81.47 vs. 5853.36 ± 97.88 s; $p = 0.0147$). Interestingly, Carb and CA frames behavior were similar in both types of surfaces (<3.9% slower in rough circuits). However, Alu was ~8% slower in the rough/bumpy courses (ES = −0.88), which might be explained by the greater shock absorption capacity of the carbon frame, which might reduce the vibration triggered by bumpy surfaces.

Surprisingly, no interaction was found between the type of the frame, the profile of the Major, and the Major's steadiness of intensity ($p = 0.9955$). Nonetheless, we found some interesting data to highlight as Alu resulted in a 6.9% slower time (392.29 s) than CA in flat courses (ES = 0.80) (Table II), which might respond to a better behavior of heavier material, as mentioned above. Nevertheless, we must be cautious with this assumption as Carb frame performance in this type of course was remarkably similar to CA (1.67% slower or ~97 s). Regarding this, ES between Alu and CA in flat courses was 0.78, which led us to speculate that characteristics of carbon seem more beneficial in flat courses and might be linked to a lower loss of mechanical energy transferred from the athlete to the frame compared to Alu. In addition, opposite to the material-surface interaction previously discussed, we found that the responses of the three materials to both types of surfaces were very homogeneous. We observed these within-material comparisons (Alu Flat vs. Hilly 1.26% slower, ES = −0.26; CA Flat vs. Hilly 1.04% slower, ES = −0.15; Carb Flat vs. Hilly 1.59% slower, ES = −0.28) (Table II). Similarly, and as mentioned in the results section, the same non-significant ($p = 0.9955$) interaction was found between the frame type and intensity steadiness. Once again, Alu performed slower than both CA and Carb in steady efforts (ES ≥ 0.78) and non-steady (ES ≥ 0.80). In this regard, it was previously published that an elite-wheeler in flat and steady efforts marathons (e.g., Oita International Wheelchair Marathon) sustained a ± 5% second ventilatory threshold intensity during the ~108 minutes which

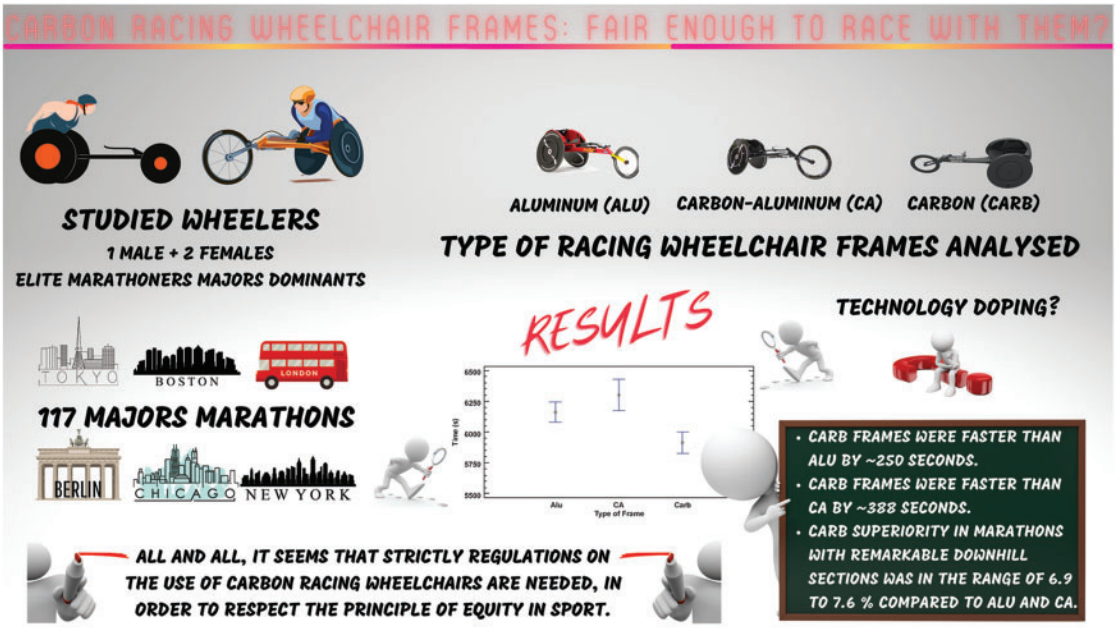

Fig. 6. Infographic of the study.

needed to win the marathon (Sanz-Quinto *et al*., 2018), what leads us to speculate that both, Carb and CA frames might maximize the preservation of muscle glycogen storage, leading to a possible greater ability to sprint at the end of the marathon (Coyle, 1995). In line with this assumption, it was reported in a randomized cross-over study a lowered metabolic demand (i.e., energy cost) between runners performing a treadmill test at 80% of maximum oxygen uptake (similar intensity to elite racing-wheelchair marathoners as previously reported by Sanz-Quinto *et al.* (2018)) with carbon plate shoes, compared to same runners wearing racing flat shoes (16.8 ± 1.5 vs. 16.3 ± 1.5 w $\cdot$ kg^{-1} or 3.07%; $p = 0.002$; ES $= 0.16$) and highly-cushioned heavier shoes (16.8 ± 1.5 vs. 16.0 ± 1.5 w $\cdot$ kg^{-1} or 5%; $p = 0.002$; ES $= 0.26$) (Hébert-Losier *et al*., 2022). Nonetheless, we must be cautious with this speculation as no energy cost was analyzed in our comparative study. Moreover, non-interaction was found between the decrease in elevation from the start line to the finish line of the Majors and the type of frame's material ($p = 0.2796$). Similar differences within materials and decrease in elevation comparisons were found with moderate ES ranging from -0.64 to 0.55 (see Table IV), being CA paradoxically slower in Majors were decrease in elevation were smaller compared to Boston (>42.192 m gained throughout the race), what remain unknown the reasons for it, as CA and Alu's frames are similar design-construction racing frames, except for the non-welded carbon main tube to the aluminum cage in CA models. In addition, it is interesting to point out that Carbon frames performance, when greater descent courses (e.g., Boston) are dominant compared to both Alu (6.9% or 412 s; ES $= 0.64$) and CA (7.6% or 455.4 s; ES $= 0.63$), what lead us to hypothesize that aerodynamics factors as frontal area and Cx, which can minimize aerodynamics drag (García-López *et al*., 2008), might be the cause of such greater performance in courses where downhills allow wheelers to reach velocities up to $\sim$80 km $\cdot$ h^{-1} (e.g., first mile at the Boston Marathon).

All in all, it seems, in terms of performance, that athletes using Carb frames would be racing under clear advantage ranging from $\sim$4% or $\sim$250 s to $\sim$6% or $\sim$388 s in Majors, compared to those taking part in these marathons with Alu and CA frames, which are $\sim$3 to $\sim$4 times cheaper, thus, more affordable for the vast majority of wheelchair athletes. Therefore, we propose the introduction of more strict regulations from the body that governs racing wheelchairs (IPC Athletics) to guarantee equity in this sport, as it has been previously suggested for road races with able-bodied runners (Burns & Tam, 2020) and finally endorsed by World Athletics (World Athletics, 2024) (see Fig. 6).

5. Conclusion

This study will help regulate the use of different types of racing wheelchairs in the marathon scenario as it has recently occurred with the athletics shoe regulations besides the lower differences reported within different types of running shoes. Interestingly, some of the previously mentioned advantages of Carb frames seem to be linked to the design-material of frames rather than to the enhancement of physiological mechanisms from athletes (e.g., in marathons where descent sections are remarkable as

Boston, Carb times compared to Alu were 6.9% faster or 412.4 s, showing ever greater advantage with CA 7.6% or 455.4 s).

On the other hand, as Carb frames are extremely expensive and almost unaffordable for the vast majority of wheelers, and these confer an unfair advantage to the few athletes who use them, we suggest that IPC Athletics introduce a compensatory timing system based on our modeling or even forbidding its use in the marathon scenario.

Finally, this potential of un-level play of field leads us to question whether Carb frames might be considered technological doping and hence become a threat to sports equity.

In order to facilitate researchers with new approaches to this paradigm (e.g., engineers who can compare frames with variables of this science background), it is mandatory to enumerate the main limitations that we have found in this study as i) the reduced number of studied athletes, however, is not an easy task to get a greater sample due to the expensiveness of Carb frames, which reduce in a significant manner the number of athletes racing with this type of material. In addition, we analyzed the best ranked wheelchair marathoners, what makes also complicated, in order to reach a larger sample size as it has previously occurred in a recently published biomechanics elite-marathoners study, in which only Eliud Kipchoge, Brigit Kosgei, and Paula Radcliffe's pacing strategies were compared (Billat *et al*., 2020), ii) in future studies, there should be compared the aerodynamic features and its relationship with the performance between different type of frames as also the estimation of metabolic demands at Majors in a cross-over study design, similar to us, what will ease a bigger picture of the controversial paradigm, iii) a limitation which could explain possible reasons for not reaching the statistical significance in the interaction material and decrease in elevation, might be the low numbers of marathons (21) included in this interaction, thus conferring low statistical power (Button *et al*., 2013) and also another reason for not reaching a significant difference may be the big heterogeneity of Carb performance in Boston (e.g., lower limit 5148.93 s and upper limit 6223.07 s), what might be explained because we analyze both genders together in the ANOVA as well as possible different windy conditions in a point-to-point marathon as Boston.

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Conflict of Interest

The authors declare no conflict of interest.

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