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## **Skyline tension and shock-loading for cable yarding with conventional single-hitch versus horizontal double-hitch suspension**

Wire rope used in cable logging, where a series of cables facilitate the extraction of timber on steep terrain, experiences high tensions that must be managed to ensure safety. Innovations in cable logging change practices over time and a recent example is the use of double-hitch carriages that allows trees to be extracted horizontally. This makes it feasible to harvest across terrain with limited deflection, increases the recovery of biomass and potentially reduces shock-load events associated with ground contact. In this study, a standard single-hitch carriage was compared against a new double-hitch carriage under controlled conditions. Tension was measured continuously and specific elements, such as midspan tension, maximum tension at breakout and inhaul, but also shock-loading events were identified and measured. These measures were compared against payload. While payload was similar in the two treatments, the additional weight of the double-hitch carriage resulted in higher skyline tensions. A strong correlation was established between payload and mid-span skyline tension for both treatments. Cyclic tension was reduced by the double-hitch carriage system. While a number of shock-loads were identified, they represented only 6% of the cycles and the maximum tension was similar to that experienced during break-out and inhaul. This study has increased the understanding of skyline tension during logging operations, and in this case specifically the effect of carriage type. Overall it also showed that while tension often exceeds the safe working load of the cable, it does not exceed the endurance limit for a well designed and operated system.

Keywords: -forestry, harvesting, safety, carriage

### **Introduction**

The need to balance cost-effective wood production with careful environmental protection and safety makes alpine forestry particularly complex (Aggestam et al. 2020). Continuous-cover forestry is popular as it mitigates hydro-geological risk while still allowing for the extraction of revenue. However, continuous-cover forestry results in low harvest volumes that reduce operation profitability (Spinelli et al. 2015).

33 Furthermore, the access constraints of a rugged mountain environment represent  
34 severe hurdles to mechanization, which is the main solution to [contain-control](#)  
35 harvesting cost despite increasing fuel price and labor wages. While full mechanization  
36 may not be feasible, modernization of cable logging practices can still offer significant  
37 benefits (Bont and Heinimann 2012; Wassermann 2018).

38 Loggers in the European Alps have increasingly moved away from motormanual  
39 delimiting and crosscutting at the stump site due to labor shortages and the need for  
40 improved work safety. Mechanized processing can reduce total harvesting cost by  
41 30%, so that stationing a processor at the yarder landing has become common practice  
42 (Spinelli et al. 2008). A number of yarder manufacturers offer mobile yarder models  
43 that integrate a boom and a processor so that the operation takes less space and becomes  
44 more economic to purchase and relocate compared with a standard two machine  
45 operation - i.e. yarder + stand-alone processor (Stampfer et al. 2006). Processing trees at  
46 the landing does not only offer the financial and safety benefits of mechanized work,  
47 but also generates additional revenue in the form of forest biomass (Valente et al. 2011),  
48 which can be delivered to a well-developed biomass market with a growing number of  
49 energy conversion plants located in many alpine settlements.

50 The system of mechanized timber processing and forest biomass recovery from  
51 yarding sites is well established; trees are processed at the landing where tops and  
52 branches accumulate, ready for recovery as energy wood. However, tree-length material  
53 is cumbersome for extraction with cable yarders in selection cuts and its extraction is  
54 only viable on relatively short distances (300-500m). Therefore, the benefits of  
55 mechanization and biomass production are currently restricted to forest areas with a  
56 good forest road network, and conversely unavailable in alpine forests not served by a  
57 suitably dense road network (Mologni et al. 2016). Such forests are normally harvested

58 with long-distance cableways which can span over one or two km down to the nearest  
59 valley road. These systems are typically rigged in a shotgun configuration (gravity  
60 return) and best suited to the extraction of short logs processed in the forest, unless  
61 sufficient deflection can be guaranteed all along the line (Samset 1985).

62 A number of tower yarder manufacturers have recently started exploring long  
63 distance extraction solutions, eventually developing new tower yarder models capable  
64 of spanning up to 1.5 km. These machines are configured for a three-cable installation  
65 because they are too large and cumbersome for moving uphill, or lack access roads to  
66 the ridges, to allow for the two-cable gravity return system. In turn, the three-cable  
67 configuration makes it possible to pull a load, even when full clearance is not achieved,  
68 thus solving the issues of tree-length harvesting. Increased extraction distance makes  
69 tree-length extraction critical again and is best offset by increasing carriage speed.

70 A tree-length load under a fast carriage may cause excessive strain of  
71 the cable set up and result in a catastrophien accident if the load hits one of the standing  
72 trees at the sides of the yarding corridor. Hence the idea of lifting trees horizontally  
73 under the carriage, suspended from two points has developed. This solution would make  
74 tree-length extraction viable on long distances regardless of yarder configuration and  
75 therefore a general technique for universal use. Double-hitch suspension requires a  
76 ‘double carriage’, composed of two separate elements working in tandem, each with its  
77 own lift line. Such carriages are already used in civil engineering for installing pipelines  
78 or other cumbersome structures in rugged terrain. However, the construction industry  
79 has different technical specifications compared with forestry and therefore the  
80 equipment used in that industry is typically too heavy and expensive for deployment in  
81 forestry. Double-hitch full-suspension technology has appeared only recently in forest

82 operations, initially as a makeshift solution improvised by loggers in the field, and later  
83 as a commercial product.

84 A number of loggers have been using the new carriages successfully for some  
85 years [in Austria, Germany, Italy and Switzerland](#). However, the definition of  
86 "successful" for a commercial logging company tends to focus on productivity, cost and  
87 reliability. The question remains about whether any of the predicted benefits on skyline  
88 tension and anchor stability has actually materialized. Loggers are not normally  
89 equipped with the precision instruments needed for measuring and monitoring those  
90 aspects, and to our knowledge no one equipped with these instruments has yet tackled  
91 the issue. Therefore, authors from many stakeholder groups gathered in a coordinated  
92 team and endeavored a study with the general objective of determining the effect of  
93 double-hitch horizontal full-suspension yarding on skyline tension and shock-loading --  
94 [the latter intended as a sudden peak in tension followed by a tension drop and a long](#)  
95 [rest \(Harrill 2014\)](#).

96 A controlled-study was carried out under the typical conditions of the forest in  
97 the Italian alps with the specific goals of: 1) determining if the skyline tension,  
98 shockloading and dynamic [solicitations-strain](#) differed significantly when the same  
99 yarder set up was equipped with a double-hitch full-suspension carriage and a standard  
100 singlehitch carriage and 2) if compliance with all safety parameters differed  
101 significantly between the two techniques, for the same payload and conditions.

## 102 **Materials and Methods**

### 103 *Materials*

104 The study was conducted in a mixed fir-spruce (*Abies alba* L. and *Picea abies* Karst.)  
105 stand in the Eastern Italian Alps, near Forni Avoltri in the Province of Udine. The stand

106 grew over a neutric cambisol soil on a south-west face and was divided in two separate  
107 belts: at the bottom of the slope and nearer to the forest road, the stand originated from  
108 the reforestation of an old pasture, carried out in the late 1950s, after farming was  
109 discontinued; further uphill and all the way to the top, the forest originated from natural  
110 regeneration and was ca. 100 years old. At the time of the study, the forest was being  
111 salvaged after the windthrow event of October 2018 that caused the loss of over 8  
112 million m<sup>3</sup> across much of North-eastern Italy (Motta et al. 2018).

113         The chainsaw operators separated windthrown trees from their root plates and  
114 crosscut the stems whenever needed for disentangling overlapping trees. Trees and tree  
115 sections were yarded downhill to the main forest road, where the yarder was installed.  
116 Once at the forest road, trees and tree sections were delimbed and cut to length using an  
117 excavator-based processor.

118         The yarder was a Valentini V600/M3/1000 trailer-mounted tower model, which  
119 is common with Alpine loggers in Austria, Germany and Italy with over 50 units sold.  
120 The machine had a maximum skyline capacity of 1000 m (22 mm cable) and was  
121 equipped with three hydraulically powered working drums, for the skyline, mainline and  
122 haulback line (22 mm, 11 mm and 11 mm, respectively). The mainline and haulback  
123 drums [contained 1100 and 2000 m of cable respectively, and](#) were fitted with a  
124 hydraulic interlock. Additional drums were available for the strawline and the guylines.  
125 The tower could telescope up to 12.5 m and during the study was fully extended. The  
126 machine was fitted with its own 175 kW diesel engine. All cables were wire rope core,  
127 swaged, ordinary lay. Skyline pre-tension was set between 100 kN and 130 kN  
128 depending on work conditions.

129         The tailhold was a large sound spruce tree, part of a solid clump of four healthy  
130 individuals. The rigging was a classic three-cable configuration, with a standing skyline,

131 a mainline and a haulback line. For the purpose of the study, the yarder was run  
132 alternately with two separate carriage set-ups: conventional clamped single-hitch  
133 carriage (henceforth: single-hitch) set for partial suspension, and unclamped motorized  
134 double-hitch dropline carriage (henceforth: double-hitch), set for full load suspension by  
135 attaching the load at two points and keeping it horizontal.

136         The single carriage was a 3-t capacity Hochleitner BW4000, weighing 760 kg.  
137 The carriage was clamped at the loading site through a hydraulic clamp and the  
138 haulback line was used for slack-pulling. Loads were hooked to the mainline by one end  
139 and were carried semi-suspended or dangling from the carriage when contact with the  
140 slope profile was interrupted (Figure 1 A).

141         The double carriage was the combination of a SEIK Skybull SFM 20/40  
142 motorized dropline (37 kW) carriage and the dedicated SEIK NL20 extension. Both the  
143 carriage and the extension carried a 2-t capacity winch, powered by the diesel engine of  
144 the Skybull 20/40 through a hydraulic transmission. Loads could be attached at two  
145 points and lifted horizontally, achieving full suspension under all conditions, with a  
146 lower load oscillation during transport (Figure 1 B). Total weight was 1000 kg,  
147 including fuel and dropline cables. During loading, the SEIK carriage combination was  
148 held in position by the mainline and the haulback line.

149

150         [Figure 1 here]

151

152         The study consisted of 74 and 75 complete cycles for the single-hitch and the  
153 double-hitch treatment, respectively. However, eight of the double-hitch cycles were  
154 excluded from the study because it was used for partial suspension only, thus violating  
155 the specifications set in the study protocol. Loads were extracted [with the same setup](#).



156 along the same ~~skyline~~ corridor and at the same pre-defined stops for both carriages, in  
157 order to guarantee even test conditions. As a matter of fact, the only thing changed for  
158 the comparison was the carriage, with the two carriages being swapped at daily  
159 intervals. ~~and a~~All extraction proceeded downhill. Total skyline length (tower tip to  
160 tailhold block) was 366 m. The horizontal distance to the tailhold was 328 m and the  
161 vertical distance was 140 m. An intermediate support was installed at a distance of 199  
162 meters from the tower in order to guarantee sufficient ground clearance along the length  
163 of the corridor.

164           The harvesting system was manned by three operators: two at the loading site  
165 (choker-setters) and one at the unloading site. The latter sat inside the cab of a processor  
166 that cut the incoming trees and tree sections into commercial assortments. The machine  
167 was a 21-t Liebherr 904 excavator fitted with a Konrad Woody 60H harvesting head.  
168 Use of radio-controlled chokers allowed the processor operator to release the load  
169 without dismounting from the machine. Both the processor operator at the unloading  
170 site by the yarder and the choker setters at the loading site in the forest could operate the  
171 yarder using a remote control, and they did so when the carriage was in their respective  
172 work areas. The remote controls were mutually exclusive, so that one operator could not  
173 interfere with the carriage movements when the carriage was outside his own defined  
174 work zone. All operators were experienced and possessed the proper formal  
175 qualifications (under the regional certification scheme).

176           The test was conducted in September 2019, and lasted a total of 23 productive  
177 machine hours (PMH), or 26 scheduled machine hours (SMH). During the test, the  
178 yarder extracted 233 m<sup>3</sup> of timber (over bark) or ca. 200 t of total biomass (timber +  
179 chips).

180 **Methods**

181 The study method aimed at determining, on a cycle basis: extraction distance, load size,  
182 time consumption, skyline tension, shock-loading and dynamic oscillations.

183 Distance between the tower and the loading point (carriage stop on the skyline)  
184 was determined using a Bushnell Yardage Pro 500 laser range finder. The terrain profile  
185 under the line was determined from the Digital Terrain Model available for the area,  
186 with a resolution of 2 m. The location of all the elements of the cable line were surveyed  
187 by a Garmin GPSmap 62 CSx hand-held GPS device, with an approximate accuracy of  
188 4 m (Morgenroth and Visser 2011).

189 Load size was obtained by scaling every single log produced from each turn,  
190 using a caliper and a measuring tape. Diameter was taken at mid-length. The species of  
191 each log was identified and recorded. Two researchers were assigned to perform this job  
192 to avoid interference in the operation. Volume measurements were converted into  
193 weight measurements after determining the actual density of the two species. For this  
194 purpose, ten logs per species were scaled and then weighed using a 9.8 kN capacity  
195 HKM HT series load cell, accurate to  $\pm 9.8$  N. The weight of the branch material was  
196 estimated by visually attributing a branch loading index to each tree or tree section as  
197 follows: a score between 0 and 4 was attributed based on the total length of the stem  
198 covered with branches (0 = no branches; 1 = branches observed on one quarter of the  
199 total length; 2 = branches observed on half of the total length etc.). Then, an additional  
200 score between 0 and 4 was attributed based on the proportion of the total circumference  
201 covered with branches, according to the same principle. The factorial combinations of  
202 the two weights yielded the following possible scores: 0, 1, 2, 3, 4, 6, 8, 9, 12, 16. The  
203 results from all observations were analyzed and the mode was extracted, which was  
204 attributed the baseline Biomass Expansion Factor (BEF) reported in bibliography for

205 windthrown spruce in the Eastern Italian Alps. This was equal to 110 kg of fresh  
206 biomass per m<sup>3</sup> of commercial timber volume (Spinelli et al. 2006). This baseline value  
207 was then corrected by the ratio between the actual combination score for each tree or  
208 tree section and the baseline weight. The individual weights for the timber and the  
209 biomass components of each piece in a load were summed into the total load weight.

210 Time was recorded with the time-and-motion technique, separated by the  
211 following tasks: unloaded carriage trip (outhaul); lowering the dropline; connecting the  
212 chokers to the load; breaking out the load and dragging it under the skyline; lifting the  
213 load under the carriage; travel loaded (inhaul); unloading; downtime - split into  
214 mechanical, operational and personnel delays (Magagnotti et al. 2013). The time study  
215 was used to reconcile tension data with specific cycle and work element information,  
216 thus providing references for identification of outhaul, breakout and inhaul.

217 Tension was recorded at 100 Hz through a 200 kN-capacity Honigmann  
218 Cablebull tension meter. The tension meter was mounted on the skyline near the  
219 tailhold, in the upper segment of the cable corridor. Tension data were downloaded into  
220 a laptop using the dedicated HCC-Easy software. A researcher was stationed by the  
221 laptop to check that data collection proceeded undisturbed. The tension meter was  
222 recalibrated four times a day during short interruptions of the work routine (beginning  
223 of work, half morning, lunch break and middle of the afternoon).

224 While monitoring provided a continuous record of tension, measurements of the  
225 following parameters were obtained from the file for each cycle and used for further  
226 analysis: pre-tension; mean tension at midspan during inhaul; peak tension at midspan  
227 during inhaul; peak tension during breakout; absolute value of shock-load, if any was  
228 recorded; magnitude of the eventual shock-load (i.e. difference between shock-load  
229 tension and tension just prior to the shock-load).

230 Tension increase (TI), tension increase factor (TI Factor) and maximum cyclic  
231 load amplitude (MCLA) were calculated as follows (Pyles et al. 1994):

232  $TI = \text{Peak tension} - \text{Skyline pre-tension}$

233  $TI \text{ Factor} = 100 * \text{Tension increase} / \text{Skyline pre-tension}$

234  $MCLA = \text{Greatest peak to peak change in skyline tension}$

235 MCLA was calculated for the tension at midspan during inhaul - when MCLA is  
236 expected to be greatest - and also at any other point during the cycle, if MCLA there  
237 was larger than recorded with the load at midspan. This eventual additional occurrence  
238 was considered a good witness for the presence of "bumps" during inhaul, caused by  
239 violent swings of the load.

240 Furthermore, shock-load was defined as a sudden peak in tension followed by a  
241 drop and a long rest (Harrill 2014), and was taken to indicate a failed attempt at  
242 disengaging a hung-up load. It described the case when the operators had to interrupt  
243 lateral skidding because the load got stuck, and they needed to reposition the carriage,  
244 change the hitch or crosscut the stem in order to get it moving. Shock-load represents a  
245 sudden and extreme tension peak, which can be especially harmful to cable integrity due  
246 to its magnitude and to its very sudden occurrence, which can generate internal friction  
247 in the cables and overheating of the component steel (OR-OSHA 1993).

248 All values were matched against the safe working load (SWL), which was  
249 calculated to be 141 kN by using a factor of safety of 3 on the published breaking load  
250 for the skyline (i.e. 424 kN divided by 3).

251 Data were extracted from the tension records of each cycle using a  
252 specifically designed R-script (R Core Team 2018). Results were then checked visually  
253 on each single graph to make sure that no unexpected occurrences had tripped the  
254 automatic system into error (Figure 2). If any inconsistencies were detected, the data

255 and the respective time stamps were checked again to resolve any doubts. This further  
256 visual check allowed confirming which cycles had actually passed the midspan. These  
257 would be expected to show a typical parabolic tension graph as the loading increases,  
258 then decreases, as the carriage passed through midspan.

259

260 [Figure 2 here]

261

262 Once checked and adjusted when required, data were analyzed statistically using  
263 the Statview software (SAS 1999). Descriptive statistics were obtained separately for  
264 each treatment. The individual work cycle (turn) was selected as the observational unit.  
265 The significance of the differences between mean values for the two treatments was  
266 tested with non-parametric techniques, which are robust against violations of the  
267 statistical assumptions (normality, homoscedasticity, data unbalance etc.). Multiple  
268 linear regression analysis allowed testing the relationship between selected dependent  
269 variables (e.g. tension at midspan, MCLA etc.) and potentially meaningful independent  
270 variables (e.g. load size, distance from the tower etc.). The effect of treatment was  
271 introduced as an indicator (dummy) variable (Olsen et al. 1998). Differences in the  
272 frequency of occurrences (e.g. shock-load events, MCLA peaks other than at midspan  
273 etc.) were tested using Chi-Square analysis. Compliance with the statistical assumptions  
274 were checked through the analysis of the residuals, which excluded serial correlation  
275 potentially deriving from gross measurement errors. In all analyses, the elected  
276 significance level was  $\alpha < 0.05$ .

277 **Results**

278 Mean extraction distance did not differ significantly between treatments, and was 183 m  
279 and 184 m for the double-hitch and the single-hitch treatment, respectively. However, the  
280 number of trips passing over the support and over midspan was significantly different  
281 between treatments, as confirmed by the Chi-square analysis (Table 1). For this reason,  
282 midspan tension was calculated only on the cycles that passed midspan. Mean load size  
283 was 8% larger for the double-hitch treatment (1,328 kg vs. 1,226 kg), but this difference  
284 was not statistically significant. However, once the weight of the carriage was factored  
285 in, the mean total weight on the skyline increased to 2,294 kg and 1,986 kg for the double-  
286 hitch and the single-hitch treatments, respectively. As a result, the difference rose to 15%  
287 and became statistically significant. The maximum recorded payload was 3,073 kg and  
288 2,820 kg for the double-hitch and the single-hitch treatment, respectively (or 4,073 kg and  
289 3,580 kg including carriage weight).

290

291 [Table 1 here]

292

293 Tension at midspan was 150 kN and 129 kN for the double-hitch and the  
294 singlehitch treatment, respectively (Table 2). Therefore, the double-hitch treatment  
295 exceeded SWL by 6%, while the single-hitch was well within it. Peak tension at  
296 midspan was not much higher than mean tension, and the single-hitch treatment still  
297 remained within SWL, although barely. However, maximum values for peak tension at  
298 midspan exceeded SWL by 29% and 16% for the double-hitch and the single-hitch  
299 treatment, respectively. MCLA at midspan was more than twice as large for the single-  
300 hitch treatment than for the double-hitch treatment. Even when recorded outside

301 midspan, MCLA was larger for the single-hitch treatment, although not as much as  
302 when at midspan (58% larger). These values account for MCLA values recorded outside  
303 midspan that 1) occurred in those cycles that did pass through midspan and 2) were  
304 greater than the MCLA measured at midspan. They were calculated and reported  
305 because they were taken to represent sudden swings of the load possibly caused by  
306 contact with the terrain.

307

308 [Table 2 here]

309

310 Regression analysis indicated that mean skyline tension at midspan increased  
311 linearly with pre-tension and payload size (Figure 3), and was 12.8 kN higher for the  
312 double-hitch treatment (Table 3). The estimated model could explain over 80% of the  
313 total variability in the dataset. A similar model (~~not reported~~) was developed for peak  
314 skyline tension at midspan, which used the same variables and was only slightly less  
315 accurate. Regression analysis also confirmed the relationship between MCLA (at  
316 midspan and outside midspan), load size and carriage treatment, but in this case the  
317 independent variable was negatively correlated with the double-hitch treatment. The  
318 explanatory power of the MCLA regressions was relatively low (30% to 47% of the  
319 total variability), but all terms were highly significant and the relationships seemed most  
320 logical. Though the MCLA models may be weak predictors, they still offer a good  
321 description of a phenomenon that is also affected by other variables not included in the  
322 survey.

323

324 [Table 3 here]

325

326 [Figure 3 here]

327

328 Chi-square analysis confirmed that shock-load events were four times more  
329 frequent with the double-hitch treatment than with the single-hitch treatment, although  
330 they were very rare occurrences anyway (10% and 2.5% of the cycles, respectively).  
331 Although less frequent, shock-loads under the single-hitch treatment reached an 8%  
332 higher tension peak and had twice the magnitude than under the double-hitch treatment  
333 (Table 4). Furthermore, the highest shock-load exceeded SWL by 19% and by 30%,  
334 under the double-hitch and the single-hitch treatment, respectively.

335

336 [Table 4 here]

337

338 The tension figures recorded for the few shock-load events were very close to  
339 those recorded for maximum lateral pull at breakout, except that the latter occurred  
340 regularly each cycle. In particular, mean peak tension at breakout was 4% higher for the  
341 double-hitch treatment (146 kN vs. 141 kN), but incurred a 5% lower TI, given the  
342 higher pre-tension value under this treatment. The maximum values recorded for  
343 breakout tension exceeded SWL by approximately 30%, with negligible differences  
344 between treatments.

## 345 Discussion

346 The study did meet its original goals of determining the differences between  
347 doublehitch horizontal yarding and conventional single-hitch yarding in terms of  
348 dynamic skyline [solicitations-stress](#) and compliance with safety standards. [In contrast,](#)  
349 [the study did not determine whether double-hitch yarding offers any specific advantages](#)



350 over long distances, given that the experimental set up covered a relatively short  
351 distance.  
352 However, that was necessary in order to limit the number of intermediate supports and  
353 facilitate tension monitoring, so that the primary objective of this study - determining  
354 skyline tension effects - could be best met.

355 As expected, the heavier double-hitch suspension carriage required a higher  
356 pretension to reach the same ground clearance. These two factors combined in a  
357 significant increase of skyline tension at midspan during inhaul compared with the  
358 conventional single-hitch carriage set up, even if payload size was not significantly  
359 larger. At the same time, reduced load swinging did result in a dramatic abatement of  
360 cyclic ~~solicitations-stress~~ - also an expected outcome. Maximum cyclic amplitude at  
361 midspan was less than half as large for the double-hitch treatment compared with the  
362 single-hitch treatment, which also explained the apparent contradiction of a higher  
363 frequency of maximum amplitude events recorded at positions different than midspan  
364 for the doublehitch treatment. Basically, minor tension spikes that would not have  
365 qualified for recording under the single-hitch treatment because they were below the  
366 amplitude measured at midspan, did so under the double-hitch treatment because the  
367 reference baseline recorded at midspan was much smaller. Although more frequent,  
368 non-midspan MCLA events recorded for the double-hitch treatment were still one third  
369 smaller than the fewer similar events recorded for the single-hitch treatment. In  
370 particular, most of these events occurred within ca. 50 m from the landing, and were  
371 likely related to a drop in the terrain profile where loads would suddenly swing from  
372 partial-suspension to full-suspension mode (Jorgensen et al. 1978). Ideally, that was not  
373 supposed to occur with the double-hitch treatment, where the load should have been  
374 fully suspended. However, even under this treatment, minor load components (tops or

375 small trees) were occasionally left hanging from one end, even if the main load was  
376 fastened at two points. Therefore, it was possible that a minor component of the load did  
377 drag on the ground even under the double-hitch treatment and then would swing out  
378 when passing over a step in the terrain profile. In that case, the small weight of the  
379 swinging component and the general better stability of the tightly fastened main load  
380 would combine in restraining cyclic load, which is what was observed in the data.

381       Concerning dynamic [strainelicitations](#), the study had the indisputable merit of  
382 producing knowledge about the frequency and magnitude of shock-loads, which is a  
383 well-known concern in cable logging but with almost no factual data published. The  
384 very high recording frequency (100 Hz) made sure that all events would be adequately  
385 captured, since shock-loads have been shown to peak most often within 0.1 to 0.2 s  
386 (Visser 1998; Harrill 2014), and older studies suggest that even a lower resolution of  
387 0.5 s could be adequate for capturing shock-loads (Jorgensen et al. 1978; Pyles et al.  
388 1994).

389       Under the conditions covered in this study, being a well-managed standing  
390 skyline setup, shock-load events were relatively rare ( $\leq 10\%$  of the cycles) and weak  
391 (max. 30% above SWL). They were weaker but more frequent under the double-hitch  
392 treatment, which can readily be explained by the smaller pulling power of the motorized  
393 carriage. Under the double-hitch treatment the dropline was powered by a separate 37  
394 kW engine, while under the single-hitch carriage treatment the pull was provided  
395 through the mainline and powered by the yarder 175 kW engine. Therefore, while the  
396 observed phenomenon was the same - i.e. a very rapid increase of tension followed by a  
397 sudden drop and a rest period - the mechanics were different. While in both instances  
398 the root cause was the load getting stuck, under the double-hitch treatment the sudden  
399 drop arrived earlier and depended on the dropline reaching its maximum pull without

400 being able to break out the load and having to give up; in contrast, under the singlehitch  
401 treatment, it was the operator who decided to stop pulling when he realized that he  
402 would break the cable or tear down an anchor if he continued. The relatively long lull  
403 period after the tension spike derived from the operator changing the hitch or  
404 crosscutting the stem to free it from the hang-up. However, even under the more  
405 aggressive single-hitch treatment, shock-loads were relatively small and always within  
406 the endurance limit (50% of minimum breaking strength: 220 kN in this specific case).

407         The same could be said for peak tension: It exceeded SWL by 30% in the worst  
408 case, which is still well within the endurance limit. Peak tension was systematically  
409 recorded at breakout, similar to all previous studies on the subject (Hartsough 1993;  
410 Pyles et al. 1994; Harrill and Visser 2013; Spinelli et al. 2017). It is during breakout that  
411 the load drags on the ground, and occasionally jams against rocks, stumps or other fixed  
412 terrain features. Jammed loads oppose a resistance that is higher than their own weight  
413 and cause tension peaks, which may turn into shock-loads if the hang-ups are not  
414 resolved and pulling must be stopped.

415         The study also produced a regression model for predicting mean skyline tension  
416 at midspan as a function of payload size. This model had a strong predictive value as  
417 accounted for over 80% of the total variability in the data. As such, it was fit to produce  
418 a reliable estimate of mean skyline tension at midspan, where tension was highest.  
419 Study data indicated that peak tension at midspan was 2% and 13% higher than mean  
420 tension, for the double-hitch and single-hitch treatment, respectively. These were the  
421 largest differences recorded in the study, and peak tension exceeded mean tension by  
422 smaller margins in general.

423         The se-results [of this study](#) are [especially](#) important because they indicate that  
424 the endurance limit of the skyline was not reached during the trial - even if SWL was

425 often exceeded during lateral skidding and inhaul. That matches the findings of another  
426 study conducted few years earlier in a similar three-cable set up also in the Italian Alps  
427 (Spinelli et al. 2017), and those of a larger observational study covering multiple  
428 installations and configurations, also performed in the same region (Mologni et al.  
429 2019). Taken together, these studies suggest that loggers in the Italian Alps (and  
430 possibly in the wider Alpine region) may operate within safe limits of wire rope  
431 capability, while occasionally exceeding legal requirements in terms of SWL. In turn,  
432 that supports the decision made by the European Standardization Agency (Technical  
433 Committee 144, Working Group 8) to decrease the skyline safety factor from 3 to 2.5  
434 for those yarders equipped with a calibrated slip brake on the skyline drum, like the  
435 machines included in this and in the 2017 study. Of course, even if the level of  
436 overloading applied by the operators in these tests is likely representative of general  
437 practice, there will always be the occasional operator who may push the envelope  
438 (Marchi et al. 2019; Mologni et al. 2019). In that regard, it is worth recalling that the  
439 study was conducted during a salvage operation, where trees had not been felled  
440 systematically according to a well-defined plan but had been pushed down over each  
441 other and were especially hard to disentangle. Under the conditions of a planned  
442 harvest, where trees are felled directionally with a view to facilitating extraction, it is  
443 likely that hang-ups would be less frequent and easier to resolve. Therefore, this study  
444 may represent a worst-case scenario. Even so, the results indicated that the tension  
445 peaks caused by dynamic loading are not as extreme as to require oversized safety  
446 factors, provided that operators act responsibly. Of course, all the considerations made  
447 above are only valid for standing skyline set ups, and cannot be extended to other  
448 configurations without proper validation.

449           Compared with the conventional single-hitch carriage, the double-hitch carriage  
450 used in this study offered the benefit of smaller shock-loads, but that was due to its less  
451 powerful dropline engine and not to any specific characteristics of the double-hitch  
452 lifting configuration. Essentially, the weaker dropline gave up earlier and at a lower  
453 tension than the stronger mainline winch, and therefore eventual shock-loads would not  
454 reach the peak values they would under the single-hitch carriage. In fact, the  
455 doublehitch carriage operated one dropline at the time during breakout, and therefore  
456 shockloads were experienced when working in a single-hitch mode. Considering that  
457 shockloads and peak skyline tension generally occur during breakout, a suitable  
458 measure to prevent excessive skyline tension could be to cap dropline (or mainline) pull.  
459 This could be a more efficient strategy than overdesigning the whole system. We now  
460 know that the problem arises during this one specific task and related to this one specific  
461 component, so it may be more economical to act on that one alone.

462           If dynamic loading is small and the weaker shock-loads experienced with the  
463 double-hitch treatment are not an inherent benefit of the double-hitch working mode,  
464 then what are the advantages of double-hitch carriages? This would be summarized as  
465 better clearance. Assuming a piece length of 20 m (taller trees are generally crosscut  
466 before yarding), double-hitch yarding would offer a clearance gain of approximately 10  
467 m, accounting for a crown radius of ca. 5 m. However, the heavier weight of the  
468 carriage would cause an increase in deflection, so some of this gain would be lost. In the  
469 case of the study set up, the midspan deflection for a mean payload of 1,300 kg, a span  
470 of 200 m, a pre-tension of 105 kN, a SWL of 141 kN and a cable weight of 2.35 kg m<sup>-1</sup>  
471 can be calculated at 8.4 m and 9.3 m for the single-hitch and the double-hitch carriage,  
472 respectively (Worksafe BC 2006). Therefore, changing to double-hitch yarding would  
473 increase clearance by ca. 9 m. Whether this benefit is worth the cost depends on the

474 specific set up and corridor; where clearance is not an issue, there is no point  
475 introducing a heavier and more expensive double-hitch carriage. Conversely, the  
476 advantage can be crucial with specific terrain profiles, and may allow shot-gunning  
477 loads downhill where that would not be feasible otherwise. For that reason, double-hitch  
478 carriages could represent an especially valuable addition to conventional sled-winch  
479 operations, which are still very popular in the Alpine area (Spinelli et al. 2013).  
480 Furthermore, double-hitch horizontal suspension would be crucial when extending cable  
481 yarding to flat terrain in sensitive sites (Erber and Spinelli 2020). In any case, it is worth  
482 noting that double-hitch carriages are designed by fitting a conventional motorized  
483 dropline carriage with a dedicated extension: the main investment remains that of the  
484 base carriage, which can easily swap configurations, thus adapting to highly variable  
485 terrain conditions.

486         Even where a three-cable configuration was set up and full suspension would not  
487 be indispensable to technical operation, minimum ground contact would have the  
488 advantage of a lower soil disturbance and a reduced branch wood contamination - the  
489 latter being especially valuable in the case of biomass recovery (Spinelli et al. 2019).  
490 However, this study was not designed to explore these further potential advantages of  
491 full suspension, and therefore any remarks in that direction remain reasonable  
492 speculation that will need to be addressed in future studies. [In fact, the operational  
493 aspects -are being covered in a separate study that compares single-hitch and  
494 doublehitch suspension in terms of productivity and cost \(Spinelli et al. 2020\).](#)

## 495 **Conclusion**

496 Few skyline tension studies have been conducted under controlled experimental  
497 conditions, despite the growing interest for the safe design and operation of cable

498 yarding equipment. Hence, the fundamental merit of this paper allows making at least  
499 two important conclusions: first, that shock-loading in a well-managed standing skyline  
500 operation is less frequent and violent than feared; second, that double-hitch horizontal  
501 suspension accrues some benefits in terms of reduced cyclic loading, but these benefits  
502 are not compelling, since cyclic loading is not extreme - even when extraction is  
503 conducted under the conventional single-hitch mode. On the other hand, double-hitch  
504 suspension offers a marked advantage in terms of increased clearance, which may be  
505 decisive when operating on broken terrain. In particular, the double-hitch option may be  
506 especially desirable for traditional sled-winch set ups that can only operate in the shot  
507 gun configuration and depend on gravity for successful downhill yarding. A smart  
508 feature of all current double-hitch carriages is their capacity to quickly convert into  
509 single-hitch motorized dropline carriages, which allows maximum operational  
510 flexibility. Finally, the study suggests that shock-load hazard could be minimized by  
511 capping dropline (or mainline) pulling power, since shock-loads are generally  
512 experienced during breakout and originate from the excessive pulling of jammed loads.  
513 Therefore, limiting pull capacity might represent a more economical measure than  
514 overdesigning the whole setup.

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524 **Declaration of interest statement**

525 No conflicts of interests to be declared.

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608 Table 1. Results of the Chi-Square analysis for the frequency of events.

Treatment		Support	No Supp	MidSpan	No Mid	Shock	No Shock
Double hitch	Actual #	45	34	54	25	8	71
	Expected #	38	41	62	17	5	74
	Contribution	1.21	1.13	1.03	3.76	4.67	0.33
Single hitch	Actual #	29	45	70	9	2	72
	Expected #	36	38	62	17	5	69
	Contribution	1.29	1.21	1.03	3.76	4.99	0.35
Chi-Square		4.83		9.59		10.34	
P-Value		0.028		0.002		0.001	

609 **Notes:** Actual # = actual count of events; Expected # = expected count of events; Contribution = contribution of  
610 factor to total Chi-Square value; Support = the cycle includes passing over the intermediate support; No Supp = the  
611 cycle includes passing over the intermediate support; Midspan = the cycle includes passing through midspan; No Mid  
612 = the cycle does not include passing through midspan; Shock = the cycle includes one shock-load event; No Shock =  
613 the cycle does not include any shock-load events;

614

615

616 Table 2. Tension at midspan.

Treatment		Double-hitch				Single-hitch				U-test
		n	Mean	Median	Max	n	Mean	Median	Max	P-Value
Midspan mean	kN	54	150	150	180	<del>6970</del>	129	128	145	<0.0001
Midspan mean TI	%	54	38	36	63	<del>6970</del>	26	25	42	<0.0001
Midspan mean/SWL	%	54	106	106	127	<del>6970</del>	91	91	103	<0.0001
Midspan Peak	kN	54	153	155	182	<del>6970</del>	138	138	164	<0.0001
Midspan Peak TI	%	54	41	41	67	<del>6970</del>	34	32	62	<0.0001
Midspan Peak/SWL	%	54	108	109	129	<del>6970</del>	97	98	116	<0.0001
MCLA midspan	kN	54	7	6	28	<del>6970</del>	17	16	52	<0.0001
MCLA non-midspan	kN	36	12	10	25	27	19	19	30	<0.0001

617 **Notes:** Midspan mean = mean tension at midspan; TI = tension increase, i.e. (tension minus pre-tension) divided by  
618 pre-tension; SWL = Safe Working Load, i.e. minimum skyline breaking strength divided by three; Midspan peak =  
619 peak tension at midspan; MCLA = Maximum cyclic load amplitude, i.e. largest peak to peak difference (in the case  
620 of midspan, MCLA = two times peak-mean); U-test = p-Value, according to Mann-Whitney non-parametric test;  
621 MCLA non-midspan = largest peak-to-peak difference if recorded when the carriage is in a position different from  
622 midspan (calculated only for those cycles that went through midspan).

623 Table 3. Regression equations for predicting tension at midspan and MCLA.

<b>Average tension at midspan</b>				
Tension (kN) = a + b * PT + c * Load + d * Double				
R <sup>2</sup> adj = 0.827, n = 121, <u>RMSE = 5.867</u>				
	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
<del>a</del> A	10.11	8.75	1.16	0.2510
<del>b</del> B	<u>1.056</u>	<u>0.083</u>	12.8	<0.0001
c	<u>0.00901</u>	<u>0.001</u>	8.95	<0.0001
<del>d</del> D	12.79	<u>1.202</u>	10.6	<0.0001
<b>Peak tension at midspan</b>				
Tension (kN) = a + b * PT + c * Load + d * Double				
R <sup>2</sup> adj = 0.688, n = 150, <u>RMSE = 7.817</u>				
	<u>Coeff</u>	<u>SE</u>	<u>T</u>	<u>P-Value</u>
<del>b</del> B	<u>0.99</u>		<u>9.74</u>	<u>&lt;0.0001</u>
<u>c</u>	<u>0.01</u>	<u>0.01</u>	<u>8.40</u>	<u>&lt;0.0001</u>
<del>d</del> D	<u>10.25</u>	<u>1.45</u>	<u>7.19</u>	<u>&lt;0.0001</u>
<b>MCLA at midspan</b>				
MCLA (kN) = a + b * Load + c * Double				
R <sup>2</sup> adj = 0.303, n = 121, <u>RMSE = 8.596</u>				
	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
<del>a</del> A	9.89	1.98	4.99	<0.0001
<del>b</del> B	<u>0.00601</u>	<u>0.001</u>	4.23	<0.0001
c	-10.45	1.59	-6.55	<0.0001
<b>MCLA not at midspan (for cycles through midspan)</b>				
MCLA (kN) = a + b * Load + c * Double				
R <sup>2</sup> adj = 0.470, n = 61, <u>RMSE = 4.807</u>				
	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
<del>a</del> A	14.72	1.55	9.47	<0.0001
<del>b</del> B	<u>0.00401</u>	<u>0.00101</u>	3.63	0.0006
c	-9.10	1.27	-7.14	<0.0001
		<u>10.75</u>		
624 <del>a</del> A	<u>23.89</u>	<u>0.10</u>	<u>2.22</u>	<u>0.0277</u>

625 **Notes:** PT = pre-tension in kN; Load = payload weight in kg; Double = Indicator variable for the double carriage = 0  
 626 if single, 1 if double; [RMS = Root mean square error \(or deviation\)](#); SE = standard error; MCLA = Maximum cyclic  
 627 load amplitude in kN

628 Table 4. Pre-tension, shock-load and maximum tension at breakout.

Treatment		Double-hitch				Single-hitch				U-test
		n	Mean	Median	Max	n	Mean	Median	Max	P-Value
Pre-tension	kN	79	109	110	120	74	103	101	111	<0.0001
Lateral Peak	kN	79	146	146	184	74	141	138	181	0.0235
Lateral TI	%	79	35	32	80	74	37	34	88	0.3899
Lateral/SWL	%	79	103	103	130	74	100	98	128	0.0235
Shock-load	kN	8	156	161	168	2	169	169	184	<0.0001
Shock Magnitude	kN	8	32	32	48	2	68	68	84	<0.0001
Shock-load TI	%	8	45	43	63	2	64	64	80	<0.0001
Shock-load/SWL	%	8	111	114	119	2	120	120	130	<0.0001

629 **Notes:** Lateral = maximum tension at breakout, during lateral pulling; TI = tension increase, i.e. (tension minus  
 630 pretension) divided by pre-tension; SWL = Safe Working Load, i.e. minimum skyline breaking strength divided by  
 631 three; Shock-load = sudden and extreme tension peak followed by a tension drop; U-test = p-Value, according to  
 632 Mann-Whitney non-parametric test.

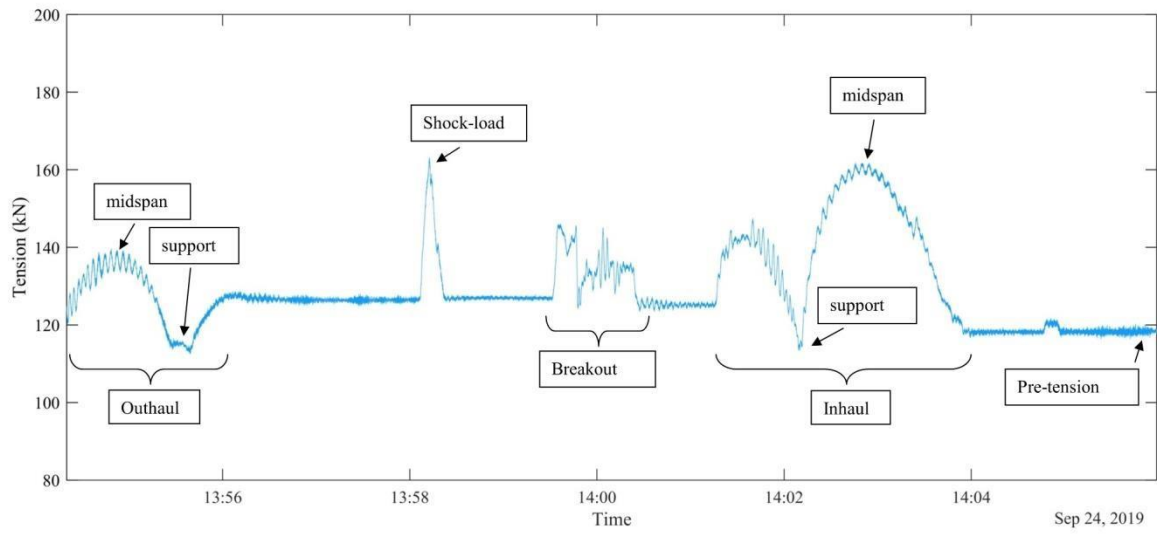
- 632 Table 1. Results of the Chi-Square analysis for the frequency of events.
- 633 Table 2. Tension at midspan.
- 634 Table 3. Regression equations for predicting tension at midspan and MCLA.
- 635 Table 4. Pre-tension, shock-load and maximum tension at breakout.



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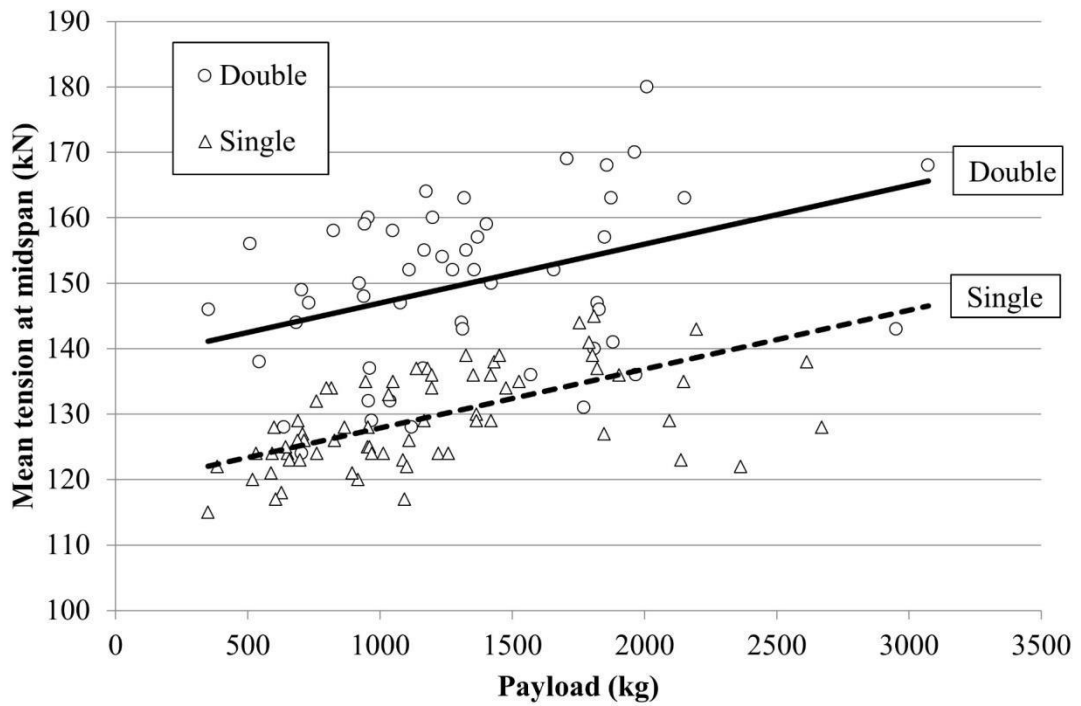
637 Figure 1. The test set-up running the single (A) and double carriage (B).





638

639 Figure 2. Example of a classic tension graph. [Note: time on the x-axis is in the](#) 640  
[hours:minutes format.](#)



641

642 Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs  
 643 were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for  
 644 the double-hitch carriage and 103 kN for the single-hitch carriage.

644 Figure 1. The test set-up running the single (A) and double carriage (B).

645 Figure 2. Example of a classic tension graph. [Note: time on the x-axis is in the](#)  
646 [hours:minutes format.](#)

647 Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs  
648 were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for  
649 the double-hitch carriage and 103 kN for the single-hitch carriage.

1 Word count: 7875 words

2

3

### 3 **Skyline tension and shock-loading for cable yarding with conventional** 4 **single-hitch versus horizontal double-hitch suspension**

5 Wire rope used in cable logging, where a series of cables facilitate the extraction  
6 of timber on steep terrain, experiences high tensions that must be managed to  
7 ensure safety. Innovations in cable logging change practices over time and a  
8 recent example is the use of double-hitch carriages that allows trees to be  
9 extracted horizontally. This makes it feasible to harvest across terrain with limited  
10 deflection, increases the recovery of biomass and potentially reduces shock-load  
11 events associated with ground contact. In this study, a standard single-hitch  
12 carriage was compared against a new double-hitch carriage under controlled  
13 conditions. Tension was measured continuously and specific elements, such as  
14 midspan tension, maximum tension at breakout and inhaul, but also shock-  
15 loading events were identified and measured. These measures were compared  
16 against payload. While payload was similar in the two treatments, the additional  
17 weight of the double-hitch carriage resulted in higher skyline tensions. A strong  
18 correlation was established between payload and mid-span skyline tension for  
19 both treatments. Cyclic tension was reduced by the double-hitch carriage system.  
20 While a number of shock-loads were identified, they represented only 6% of the  
21 cycles and the maximum tension was similar to that experienced during break-out  
22 and inhaul. This study has increased the understanding of skyline tension during  
23 logging operations, and in this case specifically the effect of carriage type.  
24 Overall it also showed that while tension often exceeds the safe working load of  
25 the cable, it does not exceed the endurance limit for a well designed and operated  
26 system.

27 Keywords: forestry, harvesting, safety, carriage

### 28 **Introduction**

29 The need to balance cost-effective wood production with careful environmental  
30 protection and safety makes alpine forestry particularly complex (Aggestam et al. 2020).  
31 Continuous-cover forestry is popular as it mitigates hydro-geological risk while still  
32 allowing for the extraction of revenue. However, continuous-cover forestry results in  
33 low harvest volumes that reduce operation profitability (Spinelli et al. 2015).

34 Furthermore, the access constraints of a rugged mountain environment represent severe  
35 hurdles to mechanization, which is the main solution to control harvesting cost despite  
36 increasing fuel price and labor wages. While full mechanization may not be feasible,  
37 modernization of cable logging practices can still offer significant benefits (Bont and  
38 Heinimann 2012; Wassermann 2018).

39         Loggers in the European Alps have increasingly moved away from motormanual  
40 delimiting and crosscutting at the stump site due to labor shortages and the need for  
41 improved work safety. Mechanized processing can reduce total harvesting cost by  
42 30%, so that stationing a processor at the yarder landing has become common practice  
43 (Spinelli et al. 2008). A number of yarder manufacturers offer mobile yarder models  
44 that integrate a boom and a processor so that the operation takes less space and becomes  
45 more economic to purchase and relocate compared with a standard two machine  
46 operation - i.e. yarder + stand-alone processor (Stampfer et al. 2006). Processing trees at  
47 the landing does not only offer the financial and safety benefits of mechanized work,  
48 but also generates additional revenue in the form of forest biomass (Valente et al. 2011),  
49 which can be delivered to a well-developed biomass market with a growing number of  
50 energy conversion plants located in many alpine settlements.

51         The system of mechanized timber processing and forest biomass recovery from  
52 yarding sites is well established; trees are processed at the landing where tops and  
53 branches accumulate, ready for recovery as energy wood. However, tree-length material  
54 is cumbersome for extraction with cable yarders in selection cuts and its extraction is  
55 only viable on relatively short distances (300-500m). Therefore, the benefits of  
56 mechanization and biomass production are currently restricted to forest areas with a  
57 good forest road network, and conversely unavailable in alpine forests not served by a  
58 suitably dense road network (Mologni et al. 2016). Such forests are normally harvested

59 with long-distance cableways which can span over one or two km down to the nearest  
60 valley road. These systems are typically rigged in a shotgun configuration (gravity  
61 return) and best suited to the extraction of short logs processed in the forest, unless  
62 sufficient deflection can be guaranteed all along the line (Samset 1985).

63 A number of tower yarder manufacturers have recently started exploring  
64 longdistance extraction solutions, eventually developing new tower yarder models  
65 capable of spanning up to 1.5 km. These machines are configured for a three-cable  
66 installation because they are too large and cumbersome for moving uphill, or lack  
67 access roads to the ridges, to allow for the two-cable gravity return system. In turn, the  
68 three-cable configuration makes it possible to pull a load, even when full clearance is  
69 not achieved, thus solving the issues of tree-length harvesting. Increased extraction  
70 distance makes tree-length extraction critical again and is best offset by increasing  
71 carriage speed.

72 A tree-length load under a fast carriage may cause excessive strain of the cable  
73 set up and result in an accident if the load hits one of the standing trees at the sides of  
74 the yarding corridor. Hence the idea of lifting trees horizontally under the carriage,  
75 suspended from two points has developed. This solution would make tree-length  
76 extraction viable on long distances regardless of yarder configuration and therefore a  
77 general technique for universal use. Double-hitch suspension requires a ‘double  
78 carriage’, composed of two separate elements working in tandem, each with its own lift  
79 line. Such carriages are already used in civil engineering for installing pipelines or other  
80 cumbersome structures in rugged terrain. However, the construction industry has  
81 different technical specifications compared with forestry and therefore the equipment  
82 used in that industry is typically too heavy and expensive for deployment in forestry.  
83 Double-hitch full-suspension technology has appeared only recently in forest

84 operations, initially as a makeshift solution improvised by loggers in the field, and later  
85 as a commercial product.

86 A number of loggers have been using the new carriages successfully for some  
87 years in Austria, Germany, Italy and Switzerland. However, the definition of  
88 "successful" for a commercial logging company tends to focus on productivity, cost and  
89 reliability. The question remains about whether any of the predicted benefits on skyline  
90 tension and anchor stability has actually materialized. Loggers are not normally  
91 equipped with the precision instruments needed for measuring and monitoring those  
92 aspects, and to our knowledge no one equipped with these instruments has yet tackled  
93 the issue. Therefore, authors from many stakeholder groups gathered in a coordinated  
94 team and endeavored a study with the general objective of determining the effect of  
95 double-hitch horizontal full-suspension yarding on skyline tension and shock-loading -  
96 the latter intended as a sudden peak in tension followed by a tension drop and a long  
97 rest (Harrill 2014).

98 A controlled-study was carried out under the typical conditions of the forest in  
99 the Italian alps with the specific goals of: 1) determining if the skyline tension,  
100 shockloading and dynamic strain differed significantly when the same yarder set up was  
101 equipped with a double-hitch full-suspension carriage and a standard single-hitch  
102 carriage and 2) if compliance with all safety parameters differed significantly between  
103 the two techniques, for the same payload and conditions.

## 104 **Materials and Methods**

### 105 *Materials*

106 The study was conducted in a mixed fir-spruce (*Abies alba* L. and *Picea abies* Karst.)  
107 stand in the Eastern Italian Alps, near Forni Avoltri in the Province of Udine. The stand



108 grew over a neutric cambisol soil on a south-west face and was divided in two separate  
109 belts: at the bottom of the slope and nearer to the forest road, the stand originated from  
110 the reforestation of an old pasture, carried out in the late 1950s, after farming was  
111 discontinued; further uphill and all the way to the top, the forest originated from natural  
112 regeneration and was ca. 100 years old. At the time of the study, the forest was being  
113 salvaged after the windthrow event of October 2018 that caused the loss of over 8  
114 million m<sup>3</sup> across much of North-eastern Italy (Motta et al. 2018).

115         The chainsaw operators separated windthrown trees from their root plates and  
116 crosscut the stems whenever needed for disentangling overlapping trees. Trees and tree  
117 sections were yarded downhill to the main forest road, where the yarder was installed.  
118 Once at the forest road, trees and tree sections were delimbed and cut to length using an  
119 excavator-based processor.

120         The yarder was a Valentini V600/M3/1000 trailer-mounted tower model, which  
121 is common with Alpine loggers in Austria, Germany and Italy with over 50 units sold.  
122 The machine had a maximum skyline capacity of 1000 m (22 mm cable) and was  
123 equipped with three hydraulically powered working drums, for the skyline, mainline and  
124 haulback line (22 mm, 11 mm and 11 mm, respectively). The mainline and haulback  
125 drums contained 1100 and 2000 m of cable respectively, and were fitted with a  
126 hydraulic interlock. Additional drums were available for the strawline and the guylines.  
127 The tower could telescope up to 12.5 m and during the study was fully extended. The  
128 machine was fitted with its own 175 kW diesel engine. All cables were wire rope core,  
129 swaged, ordinary lay. Skyline pre-tension was set between 100 kN and 130 kN  
130 depending on work conditions.

131         The tailhold was a large sound spruce tree, part of a solid clump of four healthy  
132 individuals. The rigging was a classic three-cable configuration, with a standing skyline,

133 a mainline and a haulback line. For the purpose of the study, the yarder was run  
134 alternately with two separate carriage set-ups: conventional clamped single-hitch  
135 carriage (henceforth: single-hitch) set for partial suspension, and unclamped motorized  
136 double-hitch dropline carriage (henceforth: double-hitch), set for full load suspension by  
137 attaching the load at two points and keeping it horizontal.

138         The single carriage was a 3-t capacity Hochleitner BW4000, weighing 760 kg.  
139 The carriage was clamped at the loading site through a hydraulic clamp and the  
140 haulback line was used for slack-pulling. Loads were hooked to the mainline by one end  
141 and were carried semi-suspended or dangling from the carriage when contact with the  
142 slope profile was interrupted (Figure 1 A).

143         The double carriage was the combination of a SEIK Skybull SFM 20/40  
144 motorized dropline (37 kW) carriage and the dedicated SEIK NL20 extension. Both the  
145 carriage and the extension carried a 2-t capacity winch, powered by the diesel engine of  
146 the Skybull 20/40 through a hydraulic transmission. Loads could be attached at two  
147 points and lifted horizontally, achieving full suspension under all conditions, with a  
148 lower load oscillation during transport (Figure 1 B). Total weight was 1000 kg,  
149 including fuel and dropline cables. During loading, the SEIK carriage combination was  
150 held in position by the mainline and the haulback line.

151

152         [Figure 1 here]

153

154         The study consisted of 74 and 75 complete cycles for the single-hitch and the  
155 double-hitch treatment, respectively. However, eight of the double-hitch cycles were  
156 excluded from the study because it was used for partial suspension only, thus violating  
157 the specifications set in the study protocol. Loads were extracted with the same setup,

158 along the same corridor and at the same pre-defined stops for both carriages, in order to  
159 guarantee even test conditions. As a matter of fact, the only thing changed for the  
160 comparison was the carriage, with the two carriages being swapped at daily intervals.  
161 All extraction proceeded downhill. Total skyline length (tower tip to tailhold block) was  
162 366 m. The horizontal distance to the tailhold was 328 m and the vertical distance was  
163 140 m. An intermediate support was installed at a distance of 199 meters from the tower  
164 in order to guarantee sufficient ground clearance along the length of the corridor.

165         The harvesting system was manned by three operators: two at the loading site  
166 (choker-setters) and one at the unloading site. The latter sat inside the cab of a processor  
167 that cut the incoming trees and tree sections into commercial assortments. The machine  
168 was a 21-t Liebherr 904 excavator fitted with a Konrad Woody 60H harvesting head.  
169 Use of radio-controlled chokers allowed the processor operator to release the load  
170 without dismounting from the machine. Both the processor operator at the unloading  
171 site by the yarder and the choker setters at the loading site in the forest could operate the  
172 yarder using a remote control, and they did so when the carriage was in their respective  
173 work areas. The remote controls were mutually exclusive, so that one operator could not  
174 interfere with the carriage movements when the carriage was outside his own defined  
175 work zone. All operators were experienced and possessed the proper formal  
176 qualifications (under the regional certification scheme).

177         The test was conducted in September 2019, and lasted a total of 23 productive  
178 machine hours (PMH), or 26 scheduled machine hours (SMH). During the test, the  
179 yarder extracted 233 m<sup>3</sup> of timber (over bark) or ca. 200 t of total biomass (timber +  
180 chips).

181 ***Methods***

182 The study method aimed at determining, on a cycle basis: extraction distance, load size,  
183 time consumption, skyline tension, shock-loading and dynamic oscillations.

184 Distance between the tower and the loading point (carriage stop on the skyline)  
185 was determined using a Bushnell Yardage Pro 500 laser range finder. The terrain profile  
186 under the line was determined from the Digital Terrain Model available for the area,  
187 with a resolution of 2 m. The location of all the elements of the cable line were surveyed  
188 by a Garmin GPSmap 62 CSx hand-held GPS device, with an approximate accuracy of  
189 4 m (Morgenroth and Visser 2011).

190 Load size was obtained by scaling every single log produced from each turn,  
191 using a caliper and a measuring tape. Diameter was taken at mid-length. The species of  
192 each log was identified and recorded. Two researchers were assigned to perform this job  
193 to avoid interference in the operation. Volume measurements were converted into  
194 weight measurements after determining the actual density of the two species. For this  
195 purpose, ten logs per species were scaled and then weighed using a 9.8 kN capacity  
196 HKM HT series load cell, accurate to  $\pm 9.8$  N. The weight of the branch material was  
197 estimated by visually attributing a branch loading index to each tree or tree section as  
198 follows: a score between 0 and 4 was attributed based on the total length of the stem  
199 covered with branches (0 = no branches; 1 = branches observed on one quarter of the  
200 total length; 2 = branches observed on half of the total length etc.). Then, an additional  
201 score between 0 and 4 was attributed based on the proportion of the total circumference  
202 covered with branches, according to the same principle. The factorial combinations of  
203 the two weights yielded the following possible scores: 0, 1, 2, 3, 4, 6, 8, 9, 12, 16. The  
204 results from all observations were analyzed and the mode was extracted, which was  
205 attributed the baseline Biomass Expansion Factor (BEF) reported in bibliography for

206 windthrown spruce in the Eastern Italian Alps. This was equal to 110 kg of fresh  
207 biomass per m<sup>3</sup> of commercial timber volume (Spinelli et al. 2006). This baseline value  
208 was then corrected by the ratio between the actual combination score for each tree or  
209 tree section and the baseline weight. The individual weights for the timber and the  
210 biomass components of each piece in a load were summed into the total load weight.

211 Time was recorded with the time-and-motion technique, separated by the  
212 following tasks: unloaded carriage trip (outhaul); lowering the dropline; connecting the  
213 chokers to the load; breaking out the load and dragging it under the skyline; lifting the  
214 load under the carriage; travel loaded (inhaul); unloading; downtime - split into  
215 mechanical, operational and personnel delays (Magagnotti et al. 2013). The time study  
216 was used to reconcile tension data with specific cycle and work element information,  
217 thus providing references for identification of outhaul, breakout and inhaul.

218 Tension was recorded at 100 Hz through a 200 kN-capacity Honigmann  
219 Cablebull tension meter. The tension meter was mounted on the skyline near the  
220 tailhold, in the upper segment of the cable corridor. Tension data were downloaded into  
221 a laptop using the dedicated HCC-Easy software. A researcher was stationed by the  
222 laptop to check that data collection proceeded undisturbed. The tension meter was  
223 recalibrated four times a day during short interruptions of the work routine (beginning  
224 of work, half morning, lunch break and middle of the afternoon).

225 While monitoring provided a continuous record of tension, measurements of the  
226 following parameters were obtained from the file for each cycle and used for further  
227 analysis: pre-tension; mean tension at midspan during inhaul; peak tension at midspan  
228 during inhaul; peak tension during breakout; absolute value of shock-load, if any was  
229 recorded; magnitude of the eventual shock-load (i.e. difference between shock-load  
230 tension and tension just prior to the shock-load).

231 Tension increase (TI), tension increase factor (TI Factor) and maximum cyclic  
232 load amplitude (MCLA) were calculated as follows (Pyles et al. 1994):

233  $TI = \text{Peak tension} - \text{Skyline pre-tension}$

234  $TI \text{ Factor} = 100 * \text{Tension increase} / \text{Skyline pre-tension}$

235  $MCLA = \text{Greatest peak to peak change in skyline tension}$

236 MCLA was calculated for the tension at midspan during inhaul - when MCLA is  
237 expected to be greatest - and also at any other point during the cycle, if MCLA there  
238 was larger than recorded with the load at midspan. This eventual additional occurrence  
239 was considered a good witness for the presence of "bumps" during inhaul, caused by  
240 violent swings of the load.

241 Furthermore, shock-load was defined as a sudden peak in tension followed by a  
242 drop and a long rest (Harrill 2014), and was taken to indicate a failed attempt at  
243 disengaging a hung-up load. It described the case when the operators had to interrupt  
244 lateral skidding because the load got stuck, and they needed to reposition the carriage,  
245 change the hitch or crosscut the stem in order to get it moving. Shock-load represents a  
246 sudden and extreme tension peak, which can be especially harmful to cable integrity due  
247 to its magnitude and to its very sudden occurrence, which can generate internal friction  
248 in the cables and overheating of the component steel (OR-OSHA 1993).

249 All values were matched against the safe working load (SWL), which was  
250 calculated to be 141 kN by using a factor of safety of 3 on the published breaking load  
251 for the skyline (i.e. 424 kN divided by 3).

252 Data were extracted from the tension records of each cycle using a  
253 specifically designed R-script (R Core Team 2018). Results were then checked visually  
254 on each single graph to make sure that no unexpected occurrences had tripped the  
255 automatic system into error (Figure 2). If any inconsistencies were detected, the data

256 and the respective time stamps were checked again to resolve any doubts. This further  
257 visual check allowed confirming which cycles had actually passed the midspan. These  
258 would be expected to show a typical parabolic tension graph as the loading increases,  
259 then decreases, as the carriage passed through midspan.

260

261 [Figure 2 here]

262

263 Once checked and adjusted when required, data were analyzed statistically using  
264 the Statview software (SAS 1999). Descriptive statistics were obtained separately for  
265 each treatment. The individual work cycle (turn) was selected as the observational unit.  
266 The significance of the differences between mean values for the two treatments was  
267 tested with non-parametric techniques, which are robust against violations of the  
268 statistical assumptions (normality, homoscedasticity, data unbalance etc.). Multiple  
269 linear regression analysis allowed testing the relationship between selected dependent  
270 variables (e.g. tension at midspan, MCLA etc.) and potentially meaningful independent  
271 variables (e.g. load size, distance from the tower etc.). The effect of treatment was  
272 introduced as an indicator (dummy) variable (Olsen et al. 1998). Differences in the  
273 frequency of occurrences (e.g. shock-load events, MCLA peaks other than at midspan  
274 etc.) were tested using Chi-Square analysis. Compliance with the statistical assumptions  
275 were checked through the analysis of the residuals, which excluded serial correlation  
276 potentially deriving from gross measurement errors. In all analyses, the elected  
277 significance level was  $\alpha < 0.05$ .

278 **Results**

279 Mean extraction distance did not differ significantly between treatments, and was 183 m  
280 and 184 m for the double-hitch and the single-hitch treatment, respectively. However, the  
281 number of trips passing over the support and over midspan was significantly different  
282 between treatments, as confirmed by the Chi-square analysis (Table 1). For this reason,  
283 midspan tension was calculated only on the cycles that passed midspan. Mean load size  
284 was 8% larger for the double-hitch treatment (1,328 kg vs. 1,226 kg), but this difference  
285 was not statistically significant. However, once the weight of the carriage was factored  
286 in, the mean total weight on the skyline increased to 2,294 kg and 1,986 kg for the double-  
287 hitch and the single-hitch treatments, respectively. As a result, the difference rose to 15%  
288 and became statistically significant. The maximum recorded payload was 3,073 kg and  
289 2,820 kg for the double-hitch and the single-hitch treatment, respectively (or 4,073 kg and  
290 3,580 kg including carriage weight).

291

292 [Table 1 here]

293

294 Tension at midspan was 150 kN and 129 kN for the double-hitch and the  
295 singlehitch treatment, respectively (Table 2). Therefore, the double-hitch treatment  
296 exceeded SWL by 6%, while the single-hitch was well within it. Peak tension at  
297 midspan was not much higher than mean tension, and the single-hitch treatment still  
298 remained within SWL, although barely. However, maximum values for peak tension at  
299 midspan exceeded SWL by 29% and 16% for the double-hitch and the single-hitch  
300 treatment, respectively. MCLA at midspan was more than twice as large for the single-  
301 hitch treatment than for the double-hitch treatment. Even when recorded outside



302 midspan, MCLA was larger for the single-hitch treatment, although not as much as  
303 when at midspan (58% larger). These values account for MCLA values recorded outside  
304 midspan that 1) occurred in those cycles that did pass through midspan and 2) were  
305 greater than the MCLA measured at midspan. They were calculated and reported  
306 because they were taken to represent sudden swings of the load possibly caused by  
307 contact with the terrain.

308

309 [Table 2 here]

310

311 Regression analysis indicated that mean skyline tension at midspan increased  
312 linearly with pre-tension and payload size (Figure 3), and was 12.8 kN higher for the  
313 double-hitch treatment (Table 3). The estimated model could explain over 80% of the  
314 total variability in the dataset. A similar model was developed for peak skyline tension  
315 at midspan, which used the same variables and was only slightly less accurate.

316 Regression analysis also confirmed the relationship between MCLA (at midspan and  
317 outside midspan), load size and carriage treatment, but in this case the independent  
318 variable was negatively correlated with the double-hitch treatment. The explanatory  
319 power of the MCLA regressions was relatively low (30% to 47% of the total  
320 variability), but all terms were highly significant and the relationships seemed most  
321 logical. Though the MCLA models may be weak predictors, they still offer a good  
322 description of a phenomenon that is also affected by other variables not included in the  
323 survey.

324

325 [Table 3 here]

326

327 [Figure 3 here]

328

329 Chi-square analysis confirmed that shock-load events were four times more  
330 frequent with the double-hitch treatment than with the single-hitch treatment, although  
331 they were very rare occurrences anyway (10% and 2.5% of the cycles, respectively).  
332 Although less frequent, shock-loads under the single-hitch treatment reached an 8%  
333 higher tension peak and had twice the magnitude than under the double-hitch treatment  
334 (Table 4). Furthermore, the highest shock-load exceeded SWL by 19% and by 30%,  
335 under the double-hitch and the single-hitch treatment, respectively.

336

337 [Table 4 here]

338

339 The tension figures recorded for the few shock-load events were very close to  
340 those recorded for maximum lateral pull at breakout, except that the latter occurred  
341 regularly each cycle. In particular, mean peak tension at breakout was 4% higher for the  
342 double-hitch treatment (146 kN vs. 141 kN), but incurred a 5% lower TI, given the  
343 higher pre-tension value under this treatment. The maximum values recorded for  
344 breakout tension exceeded SWL by approximately 30%, with negligible differences  
345 between treatments.

## 346 **Discussion**

347 The study did meet its original goals of determining the differences between  
348 doublehitch horizontal yarding and conventional single-hitch yarding in terms of  
349 dynamic skyline stress and compliance with safety standards. In contrast, the study did  
350 not determine whether double-hitch yarding offers any specific advantages over long  
351 distances, given that the experimental set up covered a relatively short distance.

352 However, that was necessary in order to limit the number of intermediate supports and  
353 facilitate tension monitoring, so that the primary objective of this study - determining  
354 skyline tension effects - could be best met.

355 As expected, the heavier double-hitch suspension carriage required a higher  
356 pretension to reach the same ground clearance. These two factors combined in a  
357 significant increase of skyline tension at midspan during inhaul compared with the  
358 conventional single-hitch carriage set up, even if payload size was not significantly  
359 larger. At the same time, reduced load swinging did result in a dramatic abatement of  
360 cyclic stress - also an expected outcome. Maximum cyclic amplitude at midspan was  
361 less than half as large for the double-hitch treatment compared with the single-hitch  
362 treatment, which also explained the apparent contradiction of a higher frequency of  
363 maximum amplitude events recorded at positions different than midspan for the double-  
364 hitch treatment. Basically, minor tension spikes that would not have qualified for  
365 recording under the single-hitch treatment because they were below the amplitude  
366 measured at midspan, did so under the double-hitch treatment because the reference  
367 baseline recorded at midspan was much smaller. Although more frequent, non-midspan  
368 MCLA events recorded for the double-hitch treatment were still one third smaller than  
369 the fewer similar events recorded for the single-hitch treatment. In particular, most of  
370 these events occurred within ca. 50 m from the landing, and were likely related to a drop  
371 in the terrain profile where loads would suddenly swing from partial-suspension to full-  
372 suspension mode (Jorgensen et al. 1978). Ideally, that was not supposed to occur with  
373 the double-hitch treatment, where the load should have been fully suspended. However,  
374 even under this treatment, minor load components (tops or small trees) were  
375 occasionally left hanging from one end, even if the main load was fastened at two  
376 points. Therefore, it was possible that a minor component of the load did drag on the

377 ground even under the double-hitch treatment and then would swing out when passing  
378 over a step in the terrain profile. In that case, the small weight of the swinging  
379 component and the general better stability of the tightly fastened main load would  
380 combine in restraining cyclic load, which is what was observed in the data.

381         Concerning dynamic strain, the study had the indisputable merit of producing  
382 knowledge about the frequency and magnitude of shock-loads, which is a well-known  
383 concern in cable logging but with almost no factual data published. The very high  
384 recording frequency (100 Hz) made sure that all events would be adequately captured,  
385 since shock-loads have been shown to peak most often within 0.1 to 0.2 s (Visser 1998;  
386 Harrill 2014), and older studies suggest that even a lower resolution of 0.5 s could be  
387 adequate for capturing shock-loads (Jorgensen et al. 1978; Pyles et al. 1994).

388         Under the conditions covered in this study, being a well-managed standing  
389 skyline setup, shock-load events were relatively rare ( $\leq 10\%$  of the cycles) and weak  
390 (max. 30% above SWL). They were weaker but more frequent under the double-hitch  
391 treatment, which can readily be explained by the smaller pulling power of the motorized  
392 carriage. Under the double-hitch treatment the dropline was powered by a separate 37  
393 kW engine, while under the single-hitch carriage treatment the pull was provided  
394 through the mainline and powered by the yarder 175 kW engine. Therefore, while the  
395 observed phenomenon was the same - i.e. a very rapid increase of tension followed by a  
396 sudden drop and a rest period - the mechanics were different. While in both instances  
397 the root cause was the load getting stuck, under the double-hitch treatment the sudden  
398 drop arrived earlier and depended on the dropline reaching its maximum pull without  
399 being able to break out the load and having to give up; in contrast, under the singlehitch  
400 treatment, it was the operator who decided to stop pulling when he realized that he  
401 would break the cable or tear down an anchor if he continued. The relatively long lull

402 period after the tension spike derived from the operator changing the hitch or  
403 crosscutting the stem to free it from the hang-up. However, even under the more  
404 aggressive single-hitch treatment, shock-loads were relatively small and always within  
405 the endurance limit (50% of minimum breaking strength: 220 kN in this specific case).

406         The same could be said for peak tension: It exceeded SWL by 30% in the worst  
407 case, which is still well within the endurance limit. Peak tension was systematically  
408 recorded at breakout, similar to all previous studies on the subject (Hartsough 1993;  
409 Pyles et al. 1994; Harrill and Visser 2013; Spinelli et al. 2017). It is during breakout that  
410 the load drags on the ground, and occasionally jams against rocks, stumps or other fixed  
411 terrain features. Jammed loads oppose a resistance that is higher than their own weight  
412 and cause tension peaks, which may turn into shock-loads if the hang-ups are not  
413 resolved and pulling must be stopped.

414         The study also produced a regression model for predicting mean skyline tension  
415 at midspan as a function of payload size. This model had a strong predictive value as  
416 accounted for over 80% of the total variability in the data. As such, it was fit to produce  
417 a reliable estimate of mean skyline tension at midspan, where tension was highest.  
418 Study data indicated that peak tension at midspan was 2% and 13% higher than mean  
419 tension, for the double-hitch and single-hitch treatment, respectively. These were the  
420 largest differences recorded in the study, and peak tension exceeded mean tension by  
421 smaller margins in general.

422         The results of this study are especially important because they indicate that the  
423 endurance limit of the skyline was not reached during the trial - even if SWL was often  
424 exceeded during lateral skidding and inhaul. That matches the findings of another study  
425 conducted few years earlier in a similar three-cable set up also in the Italian Alps  
426 (Spinelli et al. 2017), and those of a larger observational study covering multiple

427 installations and configurations, also performed in the same region (Mologni et al.  
428 2019). Taken together, these studies suggest that loggers in the Italian Alps (and  
429 possibly in the wider Alpine region) may operate within safe limits of wire rope  
430 capability, while occasionally exceeding legal requirements in terms of SWL. In turn,  
431 that supports the decision made by the European Standardization Agency (Technical  
432 Committee 144, Working Group 8) to decrease the skyline safety factor from 3 to 2.5  
433 for those yarders equipped with a calibrated slip brake on the skyline drum, like the  
434 machines included in this and in the 2017 study. Of course, even if the level of  
435 overloading applied by the operators in these tests is likely representative of general  
436 practice, there will always be the occasional operator who may push the envelope  
437 (Marchi et al. 2019; Mologni et al. 2019). In that regard, it is worth recalling that the  
438 study was conducted during a salvage operation, where trees had not been felled  
439 systematically according to a well-defined plan but had been pushed down over each  
440 other and were especially hard to disentangle. Under the conditions of a planned  
441 harvest, where trees are felled directionally with a view to facilitating extraction, it is  
442 likely that hang-ups would be less frequent and easier to resolve. Therefore, this study  
443 may represent a worst-case scenario. Even so, the results indicated that the tension  
444 peaks caused by dynamic loading are not as extreme as to require oversized safety  
445 factors, provided that operators act responsibly. Of course, all the considerations made  
446 above are only valid for standing skyline set ups, and cannot be extended to other  
447 configurations without proper validation.

448         Compared with the conventional single-hitch carriage, the double-hitch carriage  
449 used in this study offered the benefit of smaller shock-loads, but that was due to its less  
450 powerful dropline engine and not to any specific characteristics of the double-hitch  
451 lifting configuration. Essentially, the weaker dropline gave up earlier and at a lower

452 tension than the stronger mainline winch, and therefore eventual shock-loads would not  
453 reach the peak values they would under the single-hitch carriage. In fact, the  
454 doublehitch carriage operated one dropline at the time during breakout, and therefore  
455 shockloads were experienced when working in a single-hitch mode. Considering that  
456 shockloads and peak skyline tension generally occur during breakout, a suitable  
457 measure to prevent excessive skyline tension could be to cap dropline (or mainline) pull.  
458 This could be a more efficient strategy than overdesigning the whole system. We now  
459 know that the problem arises during this one specific task and related to this one specific  
460 component, so it may be more economical to act on that one alone.

461         If dynamic loading is small and the weaker shock-loads experienced with the  
462 double-hitch treatment are not an inherent benefit of the double-hitch working mode,  
463 then what are the advantages of double-hitch carriages? This would be summarized as  
464 better clearance. Assuming a piece length of 20 m (taller trees are generally crosscut  
465 before yarding), double-hitch yarding would offer a clearance gain of approximately 10  
466 m, accounting for a crown radius of ca. 5 m. However, the heavier weight of the  
467 carriage would cause an increase in deflection, so some of this gain would be lost. In the  
468 case of the study set up, the midspan deflection for a mean payload of 1,300 kg, a span  
469 of 200 m, a pre-tension of 105 kN, a SWL of 141 kN and a cable weight of 2.35 kg m<sup>-1</sup>  
470 can be calculated at 8.4 m and 9.3 m for the single-hitch and the double-hitch carriage,  
471 respectively (Worksafe BC 2006). Therefore, changing to double-hitch yarding would  
472 increase clearance by ca. 9 m. Whether this benefit is worth the cost depends on the  
473 specific set up and corridor; where clearance is not an issue, there is no point  
474 introducing a heavier and more expensive double-hitch carriage. Conversely, the  
475 advantage can be crucial with specific terrain profiles, and may allow shot-gunning  
476 loads downhill where that would not be feasible otherwise. For that reason, double-hitch

477 carriages could represent an especially valuable addition to conventional sled-winch  
478 operations, which are still very popular in the Alpine area (Spinelli et al. 2013).  
479 Furthermore, double-hitch horizontal suspension would be crucial when extending cable  
480 yarding to flat terrain in sensitive sites (Erber and Spinelli 2020). In any case, it is worth  
481 noting that double-hitch carriages are designed by fitting a conventional motorized  
482 dropline carriage with a dedicated extension: the main investment remains that of the  
483 base carriage, which can easily swap configurations, thus adapting to highly variable  
484 terrain conditions.

485       Even where a three-cable configuration was set up and full suspension would not  
486 be indispensable to technical operation, minimum ground contact would have the  
487 advantage of a lower soil disturbance and a reduced branch wood contamination - the  
488 latter being especially valuable in the case of biomass recovery (Spinelli et al. 2019).  
489 However, this study was not designed to explore these further potential advantages of  
490 full suspension, and therefore any remarks in that direction remain reasonable  
491 speculation that will need to be addressed in future studies. In fact, the operational  
492 aspects are being covered in a separate study that compares single-hitch and doublehitch  
493 suspension in terms of productivity and cost (Spinelli et al. 2020).

#### 494 **Conclusion**

495 Few skyline tension studies have been conducted under controlled experimental  
496 conditions, despite the growing interest for the safe design and operation of cable  
497 yarding equipment. Hence, the fundamental merit of this paper allows making at least  
498 two important conclusions: first, that shock-loading in a well-managed standing skyline  
499 operation is less frequent and violent than feared; second, that double-hitch horizontal  
500 suspension accrues some benefits in terms of reduced cyclic loading, but these benefits



501 are not compelling, since cyclic loading is not extreme - even when extraction is  
502 conducted under the conventional single-hitch mode. On the other hand, double-hitch  
503 suspension offers a marked advantage in terms of increased clearance, which may be  
504 decisive when operating on broken terrain. In particular, the double-hitch option may be  
505 especially desirable for traditional sled-winch set ups that can only operate in the shot  
506 gun configuration and depend on gravity for successful downhill yarding. A smart  
507 feature of all current double-hitch carriages is their capacity to quickly convert into  
508 single-hitch motorized dropline carriages, which allows maximum operational  
509 flexibility. Finally, the study suggests that shock-load hazard could be minimized by  
510 capping dropline (or mainline) pulling power, since shock-loads are generally  
511 experienced during breakout and originate from the excessive pulling of jammed loads.  
512 Therefore, limiting pull capacity might represent a more economical measure than  
513 overdesigning the whole setup.

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#### 523 **Declaration of interest statement**

524 No conflicts of interests to be declared.

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Table

607 1. Results of the Chi-Square analysis for the frequency of events.

Treatment		Support	No Supp	MidSpan	No Mid	Shock	No Shock
Double hitch	Actual #	45	34	54	25	8	71
	Expected #	38	41	62	17	5	74
	Contribution	1.21	1.13	1.03	3.76	4.67	0.33
Single hitch	Actual #	29	45	70	9	2	72
	Expected #	36	38	62	17	5	69
	Contribution	1.29	1.21	1.03	3.76	4.99	0.35
Chi-Square		4.83		9.59		10.34	
P-Value		0.028		0.002		0.001	

608 **Notes:** Actual # = actual count of events; Expected # = expected count of events; Contribution = contribution of  
609 factor to total Chi-Square value; Support = the cycle includes passing over the intermediate support; No Supp = the  
610 cycle includes passing over the intermediate support; Midspan = the cycle includes passing through midspan; No Mid  
611 = the cycle does not include passing through midspan; Shock = the cycle includes one shock-load event; No Shock =  
612 the cycle does not include any shock-load events;

613

614

Table

## 615 2. Tension at midspan.

Treatment		Double-hitch				Single-hitch				U-test
		n	Mean	Median	Max	n	Mean	Median	Max	P-Value
Midspan mean	kN	54	150	150	180	70	129	128	145	<0.0001
Midspan mean TI	%	54	38	36	63	70	26	25	42	<0.0001
Midspan mean/SWL	%	54	106	106	127	70	91	91	103	<0.0001
Midspan Peak	kN	54	153	155	182	70	138	138	164	<0.0001
Midspan Peak TI	%	54	41	41	67	70	34	32	62	<0.0001
Midspan Peak/SWL	%	54	108	109	129	70	97	98	116	<0.0001
MCLA midspan	kN	54	7	6	28	70	17	16	52	<0.0001
MCLA non-midspan	kN	36	12	10	25	27	19	19	30	<0.0001

616 **Notes:** Midspan mean = mean tension at midspan; TI = tension increase, i.e. (tension minus pre-tension) divided by  
617 pre-tension; SWL = Safe Working Load, i.e. minimum skyline breaking strength divided by three; Midspan peak =  
618 peak tension at midspan; MCLA = Maximum cyclic load amplitude, i.e. largest peak to peak difference (in the case  
619 of midspan, MCLA = two times peak-mean); U-test = p-Value, according to Mann-Whitney non-parametric test;  
620 MCLA non-midspan = largest peak-to-peak difference if recorded when the carriage is in a position different from  
621 midspan (calculated only for those cycles that went through midspan).

## Table

## 3. Regression equations for predicting tension at midspan and MCLA.

**Average tension at midspan**

$$\text{Tension (kN)} = a + b * \text{PT} + c * \text{Load} + d * \text{Double}$$

$$R^2 \text{ adj} = 0.827, n = 121, \text{RMSE} = 5.867$$

	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
a	10.11	8.75	1.16	0.2510
b	1.06	0.08	12.8	<0.0001
c	0.01	0.01	8.95	<0.0001
d	12.79	1.20	10.6	<0.0001

**Peak tension at midspan**

$$\text{Tension (kN)} = a + b * \text{PT} + c * \text{Load} + d * \text{Double}$$

$$R^2 \text{ adj} = 0.688, n = 150, \text{RMSE} = 7.817$$

	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
a	23.89	10.75	2.22	0.0277
b	0.99	0.10	9.74	<0.0001
c	0.01	0.01	8.40	<0.0001
d	10.25	1.45	7.19	<0.0001

**MCLA at midspan**

$$\text{MCLA (kN)} = a + b * \text{Load} + c * \text{Double}$$

$$R^2 \text{ adj} = 0.303, n = 121, \text{RMSE} = 8.596$$

	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
a	9.89	1.98	4.99	<0.0001
b	0.01	0.01	4.23	<0.0001
c	-10.45	1.59	-6.55	<0.0001

**MCLA not at midspan (for cycles through midspan)**

$$\text{MCLA (kN)} = a + b * \text{Load} + c * \text{Double}$$

$$R^2 \text{ adj} = 0.470, n = 61, \text{RMSE} = 4.807$$

	<b>Coeff</b>	<b>SE</b>	<b>T</b>	<b>P-Value</b>
a	14.72	1.55	9.47	<0.0001

Table

b	0.01	0.01	3.63	0.0006
c	-9.10	1.27	-7.14	<0.0001

623 **Notes:** PT = pre-tension in kN; Load = payload weight in kg; Double = Indicator variable for the double carriage = 0  
 624 if single, 1 if double; RMS = Root mean square error (or deviation); SE = standard error; MCLA = Maximum cyclic  
 625 load amplitude in kN

626 4. Pre-tension, shock-load and maximum tension at breakout.

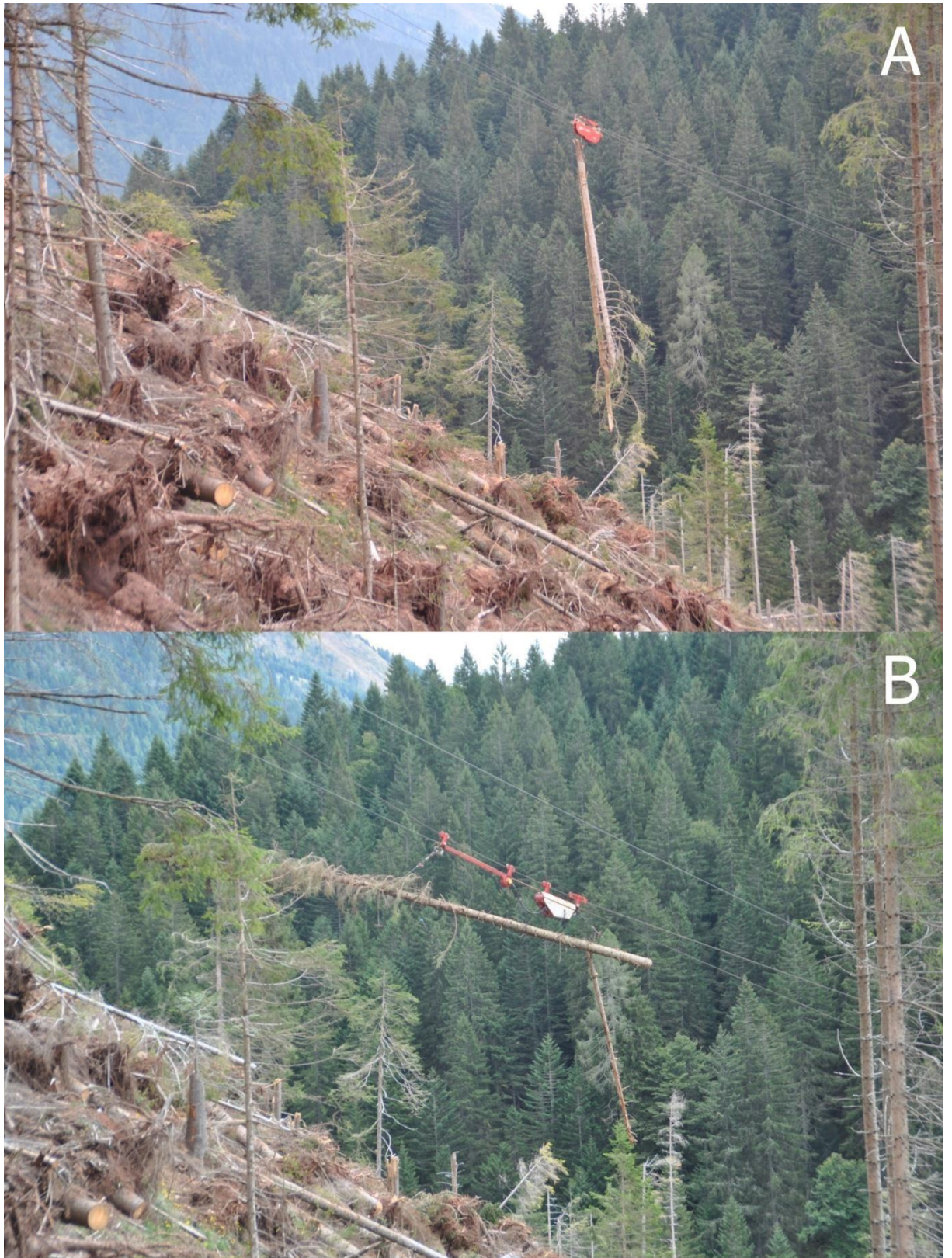
Treatment		Double-hitch				Single-hitch				U-test
		n	Mean	Median	Max	n	Mean	Median	Max	P-Value
Pre-tension	kN	79	109	110	120	74	103	101	111	<0.0001
Lateral Peak	kN	79	146	146	184	74	141	138	181	0.0235
Lateral TI	%	79	35	32	80	74	37	34	88	0.3899
Lateral/SWL	%	79	103	103	130	74	100	98	128	0.0235
Shock-load	kN	8	156	161	168	2	169	169	184	<0.0001
Shock Magnitude	kN	8	32	32	48	2	68	68	84	<0.0001
Shock-load TI	%	8	45	43	63	2	64	64	80	<0.0001
Shock-load/SWL	%	8	111	114	119	2	120	120	130	<0.0001

627 **Notes:** Lateral = maximum tension at breakout, during lateral pulling; TI = tension increase, i.e. (tension minus  
 628 pretension) divided by pre-tension; SWL = Safe Working Load, i.e. minimum skyline breaking strength divided by  
 629 three; Shock-load = sudden and extreme tension peak followed by a tension drop; U-test = p-Value, according to  
 630 Mann-Whitney non-parametric test.



Table

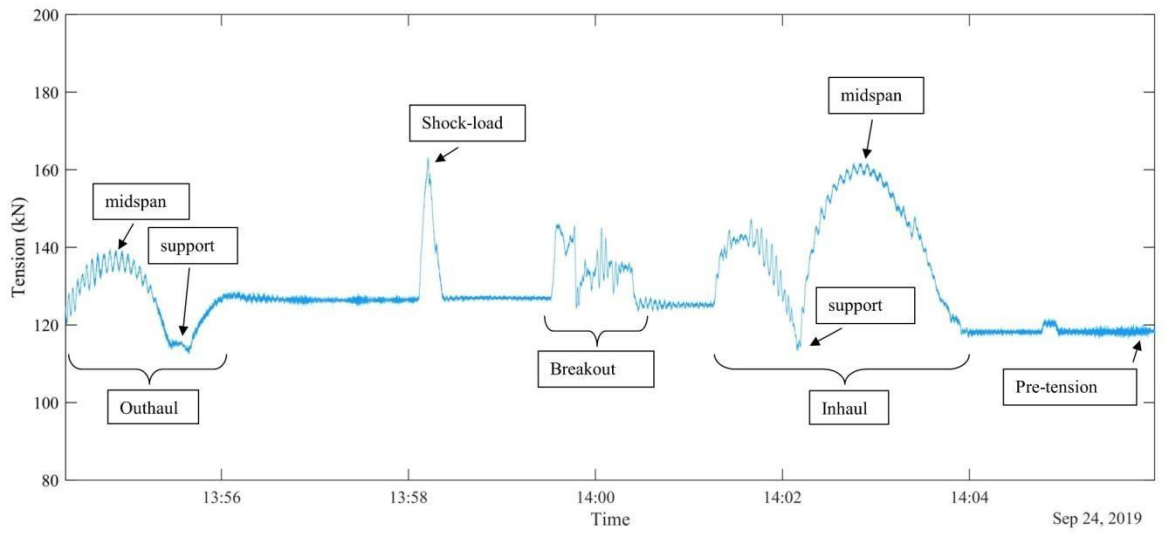
- 631 1. Results of the Chi-Square analysis for the frequency of events.
- 632 Table 2. Tension at midspan.
- 633 Table 3. Regression equations for predicting tension at midspan and MCLA.
- 634 Table 4. Pre-tension, shock-load and maximum tension at breakout.



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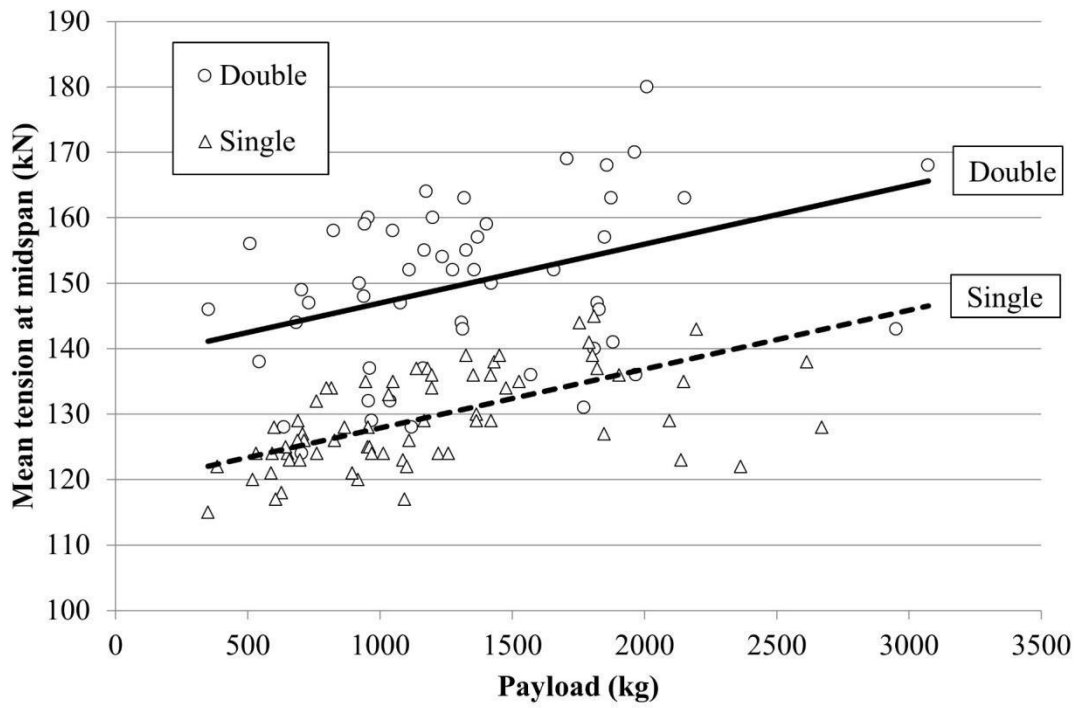
Figure 1. The test set-up running the single (A) and double carriage (B).



637

638

Figure 2. Example of a classic tension graph. Note: time on the x-axis is in the  
 639 hours:minutes format.



640

641 Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs  
 642 were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for  
 643 the double-hitch carriage and 103 kN for the single-hitch carriage.

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