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Skyline tension and dynamic loading for cable yarding comparing conventional single-hitch versus horizontal double-hitch suspension carriages

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

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

26

Keywords: -forestry, harvesting, safety, carriage

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

38 Loggers in the European Alps have increasingly moved away from motormanual 39 delimbing 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

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

A number of tower yarder manufacturers have recently started exploring long 62 63 distance extraction solutions, eventually developing new tower yarder models capable of spanning up to 1.5 km. These machines are configured for a three-cable installation 64 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 strainolicitation 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 varding 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

operations, initially as a makeshift solution improvised by loggers in the field, and lateras 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 "successful" for a commercial logging company tends to focus on productivity, cost and 86 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

grew over a neutric cambisol soil on a south-west face and was divided in two separate belts: at the bottom of the slope and nearer to the forest road, the stand originated from the reforestation of an old pasture, carried out in the late 1950s, after farming was discontinued; further uphill and all the way to the top, the forest originated from natural regeneration and was ca. 100 years old. At the time of the study, the forest was being salvaged after the windthrow event of October 2018 that caused the loss of over 8 million m³ across much of North-eastern Italy (Motta et al. 2018).

The chainsaw operators separated windthrown trees from their root plates and crosscut the stems whenever needed for disentangling overlapping trees. Trees and tree sections were yarded downhill to the main forest road, where the yarder was installed. Once at the forest road, trees and tree sections were delimbed and cut to length using an 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 healthy130 individuals. The rigging was a classic three-cable configuration, with a standing skyline,

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

The study consisted of 74 and 75 complete cycles for the single-hitch and the double-hitch treatment, respectively. However, eight of the double-hitch cycles were excluded from the study because it was used for partial suspension only, thus violating 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 aAll 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 yarder using a remote control, and they did so when the carriage was in their respective 171 172 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 varder extracted 233 m³ 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.

Distance between the tower and the loading point (carriage stop on the skyline) was determined using a Bushnell Yardage Pro 500 laser range finder. The terrain profile under the line was determined from the Digital Terrain Model available for the area, with a resolution of 2 m. The location of all the elements of the cable line were surveyed by a Garmin GPSmap 62 CSx hand-held GPS device, with an approximate accuracy of 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 ±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 the199 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 m³ 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 laptop to check that data collection proceeded undisturbed. The tension meter was 221 222 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

following parameters were obtained from the file for each cycle and used for further analysis: pre-tension; mean tension at midspan during inhaul; peak tension at midspan during inhaul; peak tension during breakout; absolute value of shock-load, if any was recorded; magnitude of the eventual shock-load (i.e. difference between shock-load 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 at al. 1994):

232 TI = Peak tension - Skyline pre-tension

233 TI Factor = 100 * Tension increase/Skyline pre-tension

234 MCLA = Greatest peak to peak change in skyline tension

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

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

Data were extracted from the tension records of each cycle using a
specificallydesigned R-script (R Core Team 2018). Results were then checked visually
on each single graph to make sure that no unexpected occurrences had tripped the

automatic system into error (Figure 2). If any inconsistencies were detected, the data

and the respective time stamps were checked again to resolve any doubts. This further
visual check allowed confirming which cycles had actually passed the midspan. These
would be expected to show a typical parabolic tension graph as the loading increases,
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 double-hitch treatment (Table 3). The estimated model could explain over 80% of the 312 313 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]

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 <u>the study did not determine whether double-hitch yarding offers any specific advantages</u>

350 over long distances, given that the experimental set up covered a relatively short

351 <u>distance.</u>

352 However, that was necessary in order to limit the number of intermediate supports and

353 <u>facilitate tension monitoring, so that the primary objective of this study - determining</u>

354 <u>skyline tension effects - could be best met.</u>

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 strainolicitations, 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 varder 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<u>se</u>-results <u>of this study</u> are <u>especially</u> 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 peaks caused by dynamic loading are not as extreme as to require oversized safety 445 446 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 of 200 m, a pre-tension of 105 kN, a SWL of 141 kN and a cable weight of 2.35 kg m⁻¹ 470 471 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 experimental497 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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Treatment	t	Support	No Supp	MidSpan	No Mid	Shock	No Shock	
Double	Actual #	45	34	54	25	8	71	
hitch	Expected #	38	41	62	17	5	74	
	Contribution	1.21	1.13	1.03	3.76	4.67	0.33	
Single	Actual #	29	45	70	9	2	72	
hitch	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		0.0	02	0.001		

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

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

Treatment		Double-hitch				Single-hitch				U-test
		n	Mean	Median	Max	n	Mean	Median	Max	P-Value
Midspan mean	kN	54	150	150	180	69 70	129	128	145	< 0.0001
Midspan mean TI	%	54	38	36	63	69 70	26	25	42	< 0.0001
Midspan mean/SWL	%	54	106	106	127	69<u>70</u>	91	91	103	< 0.0001
Midspan Peak	kN	54	153	155	182	69<u>70</u>	138	138	164	< 0.0001
Midspan Peak TI	%	54	41	41	67	69<u>70</u>	34	32	62	< 0.0001
Midspan Peak/SWL	%	54	108	109	129	69<u>70</u>	97	98	116	< 0.0001
MCLA midspan	kN	54	7	6	28	69<u>70</u>	17	16	52	< 0.0001
MCLA non-midspan	kN	36	12	10	25	27	19	19	30	< 0.0001

616 Table 2. Tension at midspan.

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).

Average tension at midspan									
Tension $(kN) = a + b * PT + c * Load + d * Double$									
R^2 adj = 0.827, n = 121, <u>RMSE = 5.867</u>									
	Coeff	SE	Т	P-Valu					
<u>a</u> A	10.11	8.75	1.16	0.2510					
<u>b</u> B	1.0 5 6	0.083	12.8	< 0.000					
c	0. 009<u>01</u>	0.001	8.95	< 0.000					
<u>d</u> Đ	12.79	1.202	10.6	< 0.000					
Peak tension at midspan									
$\underline{\text{Tension } (kN) = a + b * PT + c * Load + d * Double}$									
<u>\mathbf{R}^2 adj = 0.688, n = 150, RMSE = 7.817</u>									
	Coeff	<u>SE</u>	T	P-Valu					
<u>bB</u>	<u>0.99</u>		<u>9.74</u>	<u><0.000</u>					
<u>c</u>	0.01	0.01	<u>8.40</u>	<0.000					
₫₽	10.25	<u>1.45</u>	<u>7.19</u>	<0.000					
MCLA at midspan									
MCLA $(kN) = a + b * Load + c * Double$									
R^2 adj = 0.303, n = 121, <u>RMSE = 8.596</u>									
	Coeff	SE	Т	P-Valu					
<u>a</u> A	9.89	1.98	4.99	< 0.000					
<u>b</u> ₿	0. 006<u>01</u>	0.001	4.23	< 0.000					
c	-10.45	1.59	-6.55	< 0.000					
MCLA not at midspan (for cycles through midspan)									
MCLA $(kN) = a + b * Load + c * Double$									
R^2 adj = 0.470, n = 61 <u>, RMSE = 4.807</u>									
	Coeff	SE	Т	P-Valı					
<u>a</u> A	14.72	1.55	9.47	< 0.000					
₽₽	0. <u>00401</u>	0. 001<u>01</u>	3.63	0.000					
c	-9.10	1.27	-7.14	<0.000					
		<u>10.75</u>							
h A	23.89	0.10	2.22	0.027					

- 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; <u>RMS = Root mean square error (or deviation)</u>; <u>SE = standard error</u>; MCLA = Maximum cyclic
- 627 load amplitude in kN

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

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

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.

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





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





639 Figure 2. Example of a classic tension graph. Note: time on the x-axis is in the 640 <u>hours:minutes format</u>.



Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs
were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for
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).
- Figure 2. Example of a classic tension graph. Note: time on the x-axis is in the
 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
- the double-hitch carriage and 103 kN for the single-hitch carriage.

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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 welldesigned and operated 26 system.

27 Keywords: forestry, harvesting, safety, carriage

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

39 Loggers in the European Alps have increasingly moved away from motormanual 40 delimbing 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

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

63 A number of tower varder 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

operations, initially as a makeshift solution improvised by loggers in the field, and later
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).

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

grew over a neutric cambisol soil on a south-west face and was divided in two separate belts: at the bottom of the slope and nearer to the forest road, the stand originated from the reforestation of an old pasture, carried out in the late 1950s, after farming was discontinued; further uphill and all the way to the top, the forest originated from natural regeneration and was ca. 100 years old. At the time of the study, the forest was being salvaged after the windthrow event of October 2018 that caused the loss of over 8 million m³ across much of North-eastern Italy (Motta et al. 2018).

The chainsaw operators separated windthrown trees from their root plates and crosscut the stems whenever needed for disentangling overlapping trees. Trees and tree sections were yarded downhill to the main forest road, where the yarder was installed. Once at the forest road, trees and tree sections were delimbed and cut to length using an 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 haulback line (22 mm, 11 mm and 11 mm, respectively). The mainline and haulback 124 125 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 healthy132 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

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

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

The test was conducted in September 2019, and lasted a total of 23 productive machine hours (PMH), or 26 scheduled machine hours (SMH). During the test, the yarder extracted 233 m³ of timber (over bark) or ca. 200 t of total biomass (timber + chips).

181 Methods

189

4 m (Morgenroth and Visser 2011).

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.

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

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 ± 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 the200 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 m³ 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 laptop to check that data collection proceeded undisturbed. The tension meter was 222 223 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

following parameters were obtained from the file for each cycle and used for further analysis: pre-tension; mean tension at midspan during inhaul; peak tension at midspan during inhaul; peak tension during breakout; absolute value of shock-load, if any was recorded; magnitude of the eventual shock-load (i.e. difference between shock-load tension and tension just prior to the shock-load).

231 Tension increase (TI), tension increase factor (TI Factor) and maximum cyclic

load amplitude (MCLA) were calculated as follows (Pyles at al. 1994):

233 TI = Peak tension - Skyline pre-tension

234 TI Factor = 100 * Tension increase/Skyline pre-tension

235 MCLA = Greatest peak to peak change in skyline tension

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

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

Data were extracted from the tension records of each cycle using a specificallydesigned R-script (R Core Team 2018). Results were then checked visually on each single graph to make sure that no unexpected occurrences had tripped the

automatic system into error (Figure 2). If any inconsistencies were detected, the data

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

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

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

However, that was necessary in order to limit the number of intermediate supports and
facilitate tension monitoring, so that the primary objective of this study - determining
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.

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

The results of this study are especially important because they indicate that the endurance limit of the skyline was not reached during the trial - even if SWL was often exceeded during lateral skidding and inhaul. That matches the findings of another study conducted few years earlier in a similar three-cable set up also in the Italian Alps (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⁻¹ 470 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 varding to flat terrain in sensitive sites (Erber and Spinelli 2020). In any case, it is worth 480 481 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

Few skyline tension studies have been conducted under controlled experimental
conditions, despite the growing interest for the safe design and operation of cable
yarding equipment. Hence, the fundamental merit of this paper allows making at least
two important conclusions: first, that shock-loading in a well-managed standing skyline
operation is less frequent and violent than feared; second, that double-hitch horizontal
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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1. Results of the enr-square analysis for the frequency of events.							
Treatment		Support	No Supp	MidSpan	No Mid	Shock	No Shock
Double	Actual #	45	34	54	25	8	71
hitch	Expected #	38	41	62	17	5	74
	Contribution	1.21	1.13	1.03	3.76	4.67	0.33
Single	Actual #	29	45	70	9	2	72
hitch	Expected #	36	38	62	17	5	69
	Contribution	1.29	1.21	1.03	3.76	4.99	0.35
Chi-Square		4	.83	9.5	i9	-	10.34
P-Value		0.	028	0.0	02	(0.001

		~ . ~			
1 Do	culte of the	Chi Sauara	analysis for	• the frequ	nancy of avante
1. KU	suits of the	CIII-Square	allaly 515 101	ule neg	ucine y or evenus.

 608
 Notes: Actual # = actual count of events; Expected # = expected count of events; Contribution = contribution of

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

Table

607

	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

Average tension at midspan				
Tension $(kN) = a + b * PT + c * Load + d * Doubt$	le			
R^2 adj = 0.827, n = 121, RMSE = 5.867				
	Coeff	SE	Т	P-Valu
a	10.11	8.75	1.16	0.2510
b	1.06	0.08	12.8	< 0.000
c	0.01	0.01	8.95	< 0.000
d	12.79	1.20	10.6	< 0.000
Peak tension at midspan				
Tension $(kN) = a + b * PT + c * Load + d * Double$	le			
R^2 adj = 0.688, n = 150, RMSE = 7.817				
	Coeff	SE	Т	P-Valu
a	23.89	10.75	2.22	0.0277
b	0.99	0.10	9.74	< 0.000
c	0.01	0.01	8.40	< 0.000
d	10.25	1.45	7.19	< 0.000
MCLA at midspan				
MCLA $(kN) = a + b * Load + c * Double$				
R^2 adj = 0.303, n = 121, RMSE = 8.596				
	Coeff	SE	Т	P-Valu
a	9.89	1.98	4.99	< 0.000
b	0.01	0.01	4.23	< 0.000
c	-10.45	1.59	-6.55	< 0.000
MCLA not at midspan (for cycles through mids	span)			
MCLA $(kN) = a + b * Load + c * Double$				
$R^2 adj = 0.470, n = 61, RMSE = 4.807$				
	Coeff	SE	Т	P-Valu
0	14 72	1 55	0.47	<0.000

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.



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





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



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

- 643 Figure 1. The test set-up running the single (A) and double carriage (B).
- Figure 2. Example of a classic tension graph. Note: time on the x-axis is in thehours:minutes format.
- 646 Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs
- 647 were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for
- the double-hitch carriage and 103 kN for the single-hitch carriage.