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

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

Keywords: -forestry, harvesting, safety, carriage

Introduction

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

Furthermore, the access constraints of a rugged mountain environment represent severe hurdles to mechanization, which is the main solution to ~~contain~~ 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).

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

The system of mechanized timber processing and forest biomass recovery from yarding sites is well established; trees are processed at the landing where tops and branches accumulate, ready for recovery as energy wood. However, tree-length material is cumbersome for extraction with cable yarders in selection cuts and its extraction is only viable on relatively short distances (300-500m). Therefore, the benefits of mechanization and biomass production are currently restricted to forest areas with a good forest road network, and conversely unavailable in alpine forests not served by a 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 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 because they are too large and cumbersome for moving uphill, or lack access roads to the ridges, to allow for the two-cable gravity return system. In turn, the three-cable configuration makes it possible to pull a load, even when full clearance is not achieved, thus solving the issues of tree-length harvesting. Increased extraction distance makes tree-length extraction critical again and is best offset by increasing carriage speed.

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

A number of loggers have been using the new carriages successfully for some years in Austria, Germany, Italy and Switzerland. However, the definition of "successful" for a commercial logging company tends to focus on productivity, cost and reliability. The question remains about whether any of the predicted benefits on skyline tension and anchor stability has actually materialized. Loggers are not normally equipped with the precision instruments needed for measuring and monitoring those aspects, and to our knowledge no one equipped with these instruments has yet tackled the issue. Therefore, authors from many stakeholder groups gathered in a coordinated team and endeavored a study with the general objective of determining the effect of double-hitch horizontal full-suspension yarding on skyline tension and shock-loading -- the latter intended as a sudden peak in tension followed by a tension drop and a long 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 ~~solicitations~~ strain differed significantly when the same yarder set up was equipped with a double-hitch full-suspension carriage and a standard singlehitch carriage and 2) if compliance with all safety parameters differed significantly between the two techniques, for the same payload and conditions.

Materials and Methods

Materials

The study was conducted in a mixed fir-spruce (Abies alba L. and Picea abies Karst.) 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 m^3 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.

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

The tailhold was a large sound spruce tree, part of a solid clump of four healthy 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. The carriage was clamped at the loading site through a hydraulic clamp and the haulback line was used for slack-pulling. Loads were hooked to the mainline by one end and were carried semi-suspended or dangling from the carriage when contact with the slope profile was interrupted (Figure 1 A).

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

[Figure 1 here]

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 ~~skyline~~ 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. ~~and a~~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.

The harvesting system was manned by three operators: two at the loading site (choker-setters) and one at the unloading site. The latter sat inside the cab of a processor that cut the incoming trees and tree sections into commercial assortments. The machine was a 21-t Liebherr 904 excavator fitted with a Konrad Woody 60H harvesting head. Use of radio-controlled chokers allowed the processor operator to release the load without dismounting from the machine. Both the processor operator at the unloading 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 work areas. The remote controls were mutually exclusive, so that one operator could not interfere with the carriage movements when the carriage was outside his own defined work zone. All operators were experienced and possessed the proper formal 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 m^3 of timber (over bark) or ca. 200 t of total biomass (timber + chips).

Methods

The study method aimed at determining, on a cycle basis: extraction distance, load size, 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).

Load size was obtained by scaling every single log produced from each turn, using a caliper and a measuring tape. Diameter was taken at mid-length. The species of each log was identified and recorded. Two researchers were assigned to perform this job to avoid interference in the operation. Volume measurements were converted into weight measurements after determining the actual density of the two species. For this purpose, ten logs per species were scaled and then weighed using a 9.8 kN capacity HKM HT series load cell, accurate to ±9.8 N. The weight of the branch material was estimated by visually attributing a branch loading index to each tree or tree section as follows: a score between 0 and 4 was attributed based on the total length of the stem covered with branches (0 = no branches; 1 = branches observed on one quarter of the total length; 2 = branches observed on half of the total length etc.). Then, an additional score between 0 and 4 was attributed based on the proportion of the total circumference covered with branches, according to the same principle. The factorial combinations of the two weights yielded the following possible scores: 0, 1, 2, 3, 4, 6, 8, 9, 12, 16. The results from all observations were analyzed and the mode was extracted, which was attributed the baseline Biomass Expansion Factor (BEF) reported in bibliography for windthrown spruce in the Eastern Italian Alps. This was equal to 110 kg of fresh biomass per m^3 of commercial timber volume (Spinelli et al. 2006). This baseline value was then corrected by the ratio between the actual combination score for each tree or tree section and the baseline weight. The individual weights for the timber and the biomass components of each piece in a load were summed into the total load weight.

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

Tension was recorded at 100 Hz through a 200 kN-capacity Honigmann Cablebull tension meter. The tension meter was mounted on the skyline near the tailhold, in the upper segment of the cable corridor. Tension data were downloaded into 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 recalibrated four times a day during short interruptions of the work routine (beginning of work, half morning, lunch break and middle of the afternoon).

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).

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

TI = Peak tension - Skyline pre-tension

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

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.

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

[Figure 2 here]

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

Results

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

[Table 1 here]

Tension at midspan was 150 kN and 129 kN for the double-hitch and the singlehitch treatment, respectively (Table 2). Therefore, the double-hitch treatment exceeded SWL by 6%, while the single-hitch was well within it. Peak tension at midspan was not much higher than mean tension, and the single-hitch treatment still remained within SWL, although barely. However, maximum values for peak tension at midspan exceeded SWL by 29% and 16% for the double-hitch and the single-hitch treatment, respectively. MCLA at midspan was more than twice as large for the single-hitch treatment than for the double-hitch treatment. Even when recorded outside midspan, MCLA was larger for the single-hitch treatment, although not as much as when at midspan (58% larger). These values account for MCLA values recorded outside midspan that 1) occurred in those cycles that did pass through midspan and 2) were greater than the MCLA measured at midspan. They were calculated and reported because they were taken to represent sudden swings of the load possibly caused by contact with the terrain.

[Table 2 here]

Regression analysis indicated that mean skyline tension at midspan increased 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 total variability in the dataset. A similar model ~~(not reported)~~ was developed for peak skyline tension at midspan, which used the same variables and was only slightly less accurate. Regression analysis also confirmed the relationship between MCLA (at midspan and outside midspan), load size and carriage treatment, but in this case the independent variable was negatively correlated with the double-hitch treatment. The explanatory power of the MCLA regressions was relatively low (30% to 47% of the total variability), but all terms were highly significant and the relationships seemed most logical. Though the MCLA models may be weak predictors, they still offer a good description of a phenomenon that is also affected by other variables not included in the survey.

[Table 3 here]

[Figure 3 here]

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

[Table 4 here]

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

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 ~~solicitations~~ 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.

As expected, the heavier double-hitch suspension carriage required a higher pretension to reach the same ground clearance. These two factors combined in a significant increase of skyline tension at midspan during inhaul compared with the conventional single-hitch carriage set up, even if payload size was not significantly larger. At the same time, reduced load swinging did result in a dramatic abatement of cyclic ~~solicitations~~ stress - also an expected outcome. Maximum cyclic amplitude at midspan was less than half as large for the double-hitch treatment compared with the single-hitch treatment, which also explained the apparent contradiction of a higher frequency of maximum amplitude events recorded at positions different than midspan for the doublehitch treatment. Basically, minor tension spikes that would not have qualified for recording under the single-hitch treatment because they were below the amplitude measured at midspan, did so under the double-hitch treatment because the reference baseline recorded at midspan was much smaller. Although more frequent, non-midspan MCLA events recorded for the double-hitch treatment were still one third smaller than the fewer similar events recorded for the single-hitch treatment. In particular, most of these events occurred within ca. 50 m from the landing, and were likely related to a drop in the terrain profile where loads would suddenly swing from partial-suspension to full-suspension mode (Jorgensen et al. 1978). Ideally, that was not supposed to occur with the double-hitch treatment, where the load should have been fully suspended. However, even under this treatment, minor load components (tops or small trees) were occasionally left hanging from one end, even if the main load was fastened at two points. Therefore, it was possible that a minor component of the load did drag on the ground even under the double-hitch treatment and then would swing out when passing over a step in the terrain profile. In that case, the small weight of the swinging component and the general better stability of the tightly fastened main load would combine in restraining cyclic load, which is what was observed in the data.

Concerning dynamic strain~~olicitations~~, 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).

Under the conditions covered in this study, being a well-managed standing skyline setup, shock-load events were relatively rare (≤ 10% of the cycles) and weak (max. 30% above SWL). They were weaker but more frequent under the double-hitch treatment, which can readily be explained by the smaller pulling power of the motorized carriage. Under the double-hitch treatment the dropline was powered by a separate 37 kW engine, while under the single-hitch carriage treatment the pull was provided through the mainline and powered by the yarder 175 kW engine. Therefore, while the observed phenomenon was the same - i.e. a very rapid increase of tension followed by a sudden drop and a rest period - the mechanics were different. While in both instances the root cause was the load getting stuck, under the double-hitch treatment the sudden drop arrived earlier and depended on the dropline reaching its maximum pull without being able to break out the load and having to give up; in contrast, under the singlehitch treatment, it was the operator who decided to stop pulling when he realized that he would break the cable or tear down an anchor if he continued. The relatively long lull period after the tension spike derived from the operator changing the hitch or crosscutting the stem to free it from the hang-up. However, even under the more aggressive single-hitch treatment, shock-loads were relatively small and always within the endurance limit (50% of minimum breaking strength: 220 kN in this specific case).

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

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

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

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

If dynamic loading is small and the weaker shock-loads experienced with the double-hitch treatment are not an inherent benefit of the double-hitch working mode, then what are the advantages of double-hitch carriages? This would be summarized as better clearance. Assuming a piece length of 20 m (taller trees are generally crosscut before yarding), double-hitch yarding would offer a clearance gain of approximately 10 m, accounting for a crown radius of ca. 5 m. However, the heavier weight of the carriage would cause an increase in deflection, so some of this gain would be lost. In the 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} can be calculated at 8.4 m and 9.3 m for the single-hitch and the double-hitch carriage, respectively (Worksafe BC 2006). Therefore, changing to double-hitch yarding would increase clearance by ca. 9 m. Whether this benefit is worth the cost depends on the specific set up and corridor; where clearance is not an issue, there is no point introducing a heavier and more expensive double-hitch carriage. Conversely, the advantage can be crucial with specific terrain profiles, and may allow shot-gunning loads downhill where that would not be feasible otherwise. For that reason, double-hitch carriages could represent an especially valuable addition to conventional sled-winch operations, which are still very popular in the Alpine area (Spinelli et al. 2013). Furthermore, double-hitch horizontal suspension would be crucial when extending cable yarding to flat terrain in sensitive sites (Erber and Spinelli 2020). In any case, it is worth noting that double-hitch carriages are designed by fitting a conventional motorized dropline carriage with a dedicated extension: the main investment remains that of the base carriage, which can easily swap configurations, thus adapting to highly variable terrain conditions.

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

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

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Declaration of interest statement

No conflicts of interests to be declared.

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

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

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 cycle includes passing over the intermediate support; Midspan = the cycle includes passing through midspan; No Mid = the cycle does not include passing through midspan; Shock = the cycle includes one shock-load event; No Shock = the cycle does not include any shock-load events;

Table 2. Tension at midspan.

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

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

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

Average tension at midspan

Tension (kN) = a + b * PT + c * Load + d * Double

R^2 adj = 0.827, n = 121, RMSE = 5.867

	Coeff	SE	T	P-Value
aA	10.11	8.75	1.16	0.2510
bB	1.056	0.083	12.8	<0.0001
c	0.00901	0.001	8.95	<0.0001
dD	12.79	1.202	10.6	<0.0001

Peak tension at midspan

Tension (kN) = a + b * PT + c * Load + d * Double

R^2 adj = 0.688, n = 150, RMSE = 7.817

	Coeff	SE	T	P-Value
bB	0.99		9.74	<0.0001
c	0.01	0.01	8.40	<0.0001
dD	10.25	1.45	7.19	<0.0001

MCLA at midspan

MCLA (kN) = a + b * Load + c * Double

R^2 adj = 0.303, n = 121, RMSE = 8.596

	Coeff	SE	T	P-Value
aA	9.89	1.98	4.99	<0.0001
bB	0.00601	0.001	4.23	<0.0001
c	-10.45	1.59	-6.55	<0.0001

MCLA not at midspan (for cycles through midspan)

MCLA (kN) = a + b * Load + c * Double

R^2 adj = 0.470, n = 61, RMSE = 4.807

	Coeff	SE	T	P-Value
aA	14.72	1.55	9.47	<0.0001
bB	0.00401	0.00101	3.63	0.0006
c	-9.10	1.27	-7.14	<0.0001
aA	23.89	10.75 0.10	2.22	0.0277

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

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

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

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

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

Table 2. Tension at midspan.

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

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).

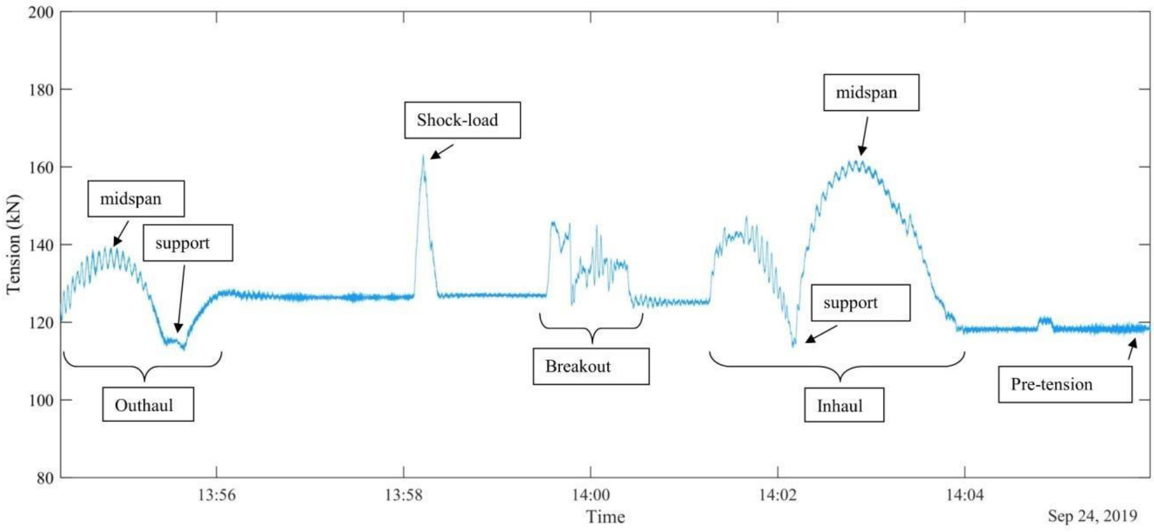

Figure 2. Example of a classic tension graph. Note: time on the x-axis is in the hours:minutes format.

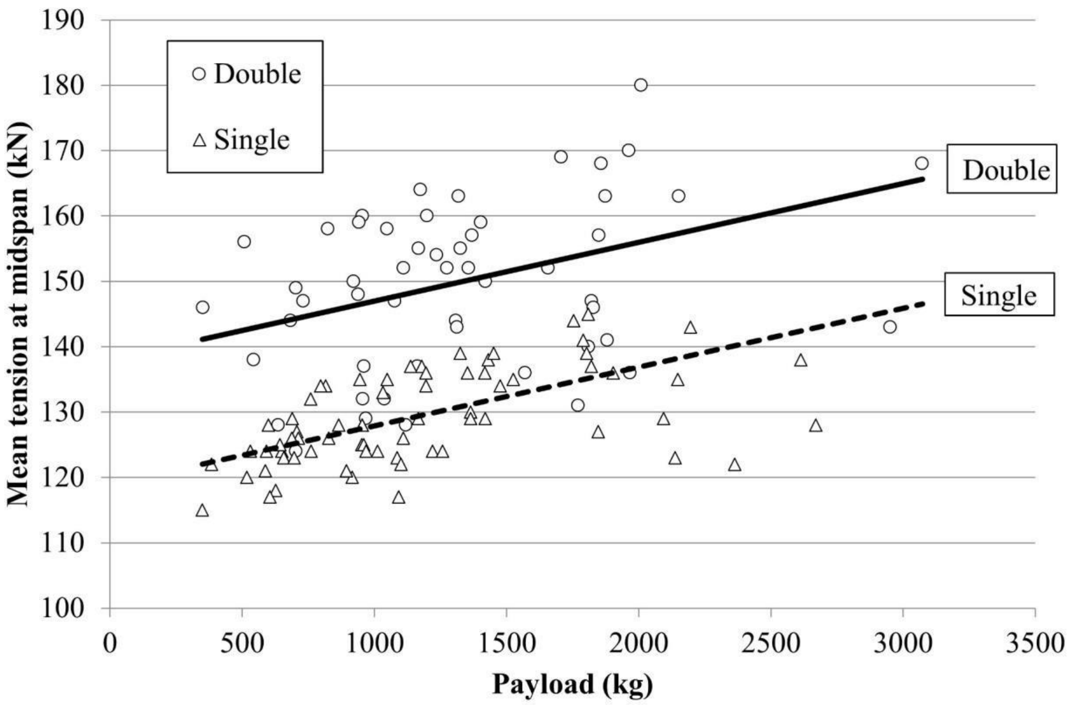

Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for the double-hitch carriage and 103 kN for the single-hitch carriage.

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.

Word count: 7875 words

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

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

Keywords: forestry, harvesting, safety, carriage

Introduction

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

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).

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

The system of mechanized timber processing and forest biomass recovery from yarding sites is well established; trees are processed at the landing where tops and branches accumulate, ready for recovery as energy wood. However, tree-length material is cumbersome for extraction with cable yarders in selection cuts and its extraction is only viable on relatively short distances (300-500m). Therefore, the benefits of mechanization and biomass production are currently restricted to forest areas with a good forest road network, and conversely unavailable in alpine forests not served by a 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 longdistance 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 because they are too large and cumbersome for moving uphill, or lack access roads to the ridges, to allow for the two-cable gravity return system. In turn, the three-cable configuration makes it possible to pull a load, even when full clearance is not achieved, thus solving the issues of tree-length harvesting. Increased extraction distance makes tree-length extraction critical again and is best offset by increasing carriage speed.

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

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

Materials and Methods

Materials

The study was conducted in a mixed fir-spruce (Abies alba L. and Picea abies Karst.) 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 m^3 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.

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

The tailhold was a large sound spruce tree, part of a solid clump of four healthy 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. The carriage was clamped at the loading site through a hydraulic clamp and the haulback line was used for slack-pulling. Loads were hooked to the mainline by one end and were carried semi-suspended or dangling from the carriage when contact with the slope profile was interrupted (Figure 1 A).

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

[Figure 1 here]

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.

The harvesting system was manned by three operators: two at the loading site (choker-setters) and one at the unloading site. The latter sat inside the cab of a processor that cut the incoming trees and tree sections into commercial assortments. The machine was a 21-t Liebherr 904 excavator fitted with a Konrad Woody 60H harvesting head. Use of radio-controlled chokers allowed the processor operator to release the load without dismounting from the machine. Both the processor operator at the unloading 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 work areas. The remote controls were mutually exclusive, so that one operator could not interfere with the carriage movements when the carriage was outside his own defined work zone. All operators were experienced and possessed the proper formal 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 m^3 of timber (over bark) or ca. 200 t of total biomass (timber + chips).

Methods

The study method aimed at determining, on a cycle basis: extraction distance, load size, 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).

Load size was obtained by scaling every single log produced from each turn, using a caliper and a measuring tape. Diameter was taken at mid-length. The species of each log was identified and recorded. Two researchers were assigned to perform this job to avoid interference in the operation. Volume measurements were converted into weight measurements after determining the actual density of the two species. For this purpose, ten logs per species were scaled and then weighed using a 9.8 kN capacity HKM HT series load cell, accurate to ±9.8 N. The weight of the branch material was estimated by visually attributing a branch loading index to each tree or tree section as follows: a score between 0 and 4 was attributed based on the total length of the stem covered with branches (0 = no branches; 1 = branches observed on one quarter of the total length; 2 = branches observed on half of the total length etc.). Then, an additional score between 0 and 4 was attributed based on the proportion of the total circumference covered with branches, according to the same principle. The factorial combinations of the two weights yielded the following possible scores: 0, 1, 2, 3, 4, 6, 8, 9, 12, 16. The results from all observations were analyzed and the mode was extracted, which was attributed the baseline Biomass Expansion Factor (BEF) reported in bibliography for windthrown spruce in the Eastern Italian Alps. This was equal to 110 kg of fresh biomass per m^3 of commercial timber volume (Spinelli et al. 2006). This baseline value was then corrected by the ratio between the actual combination score for each tree or tree section and the baseline weight. The individual weights for the timber and the biomass components of each piece in a load were summed into the total load weight.

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

Tension was recorded at 100 Hz through a 200 kN-capacity Honigmann Cablebull tension meter. The tension meter was mounted on the skyline near the tailhold, in the upper segment of the cable corridor. Tension data were downloaded into 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 recalibrated four times a day during short interruptions of the work routine (beginning of work, half morning, lunch break and middle of the afternoon).

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).

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

TI = Peak tension - Skyline pre-tension

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

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.

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

[Figure 2 here]

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

Results

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

[Table 1 here]

Tension at midspan was 150 kN and 129 kN for the double-hitch and the singlehitch treatment, respectively (Table 2). Therefore, the double-hitch treatment exceeded SWL by 6%, while the single-hitch was well within it. Peak tension at midspan was not much higher than mean tension, and the single-hitch treatment still remained within SWL, although barely. However, maximum values for peak tension at midspan exceeded SWL by 29% and 16% for the double-hitch and the single-hitch treatment, respectively. MCLA at midspan was more than twice as large for the single-hitch treatment than for the double-hitch treatment. Even when recorded outside midspan, MCLA was larger for the single-hitch treatment, although not as much as when at midspan (58% larger). These values account for MCLA values recorded outside midspan that 1) occurred in those cycles that did pass through midspan and 2) were greater than the MCLA measured at midspan. They were calculated and reported because they were taken to represent sudden swings of the load possibly caused by contact with the terrain.

[Table 2 here]

Regression analysis indicated that mean skyline tension at midspan increased 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 total variability in the dataset. A similar model was developed for peak skyline tension at midspan, which used the same variables and was only slightly less accurate. Regression analysis also confirmed the relationship between MCLA (at midspan and outside midspan), load size and carriage treatment, but in this case the independent variable was negatively correlated with the double-hitch treatment. The explanatory power of the MCLA regressions was relatively low (30% to 47% of the total variability), but all terms were highly significant and the relationships seemed most logical. Though the MCLA models may be weak predictors, they still offer a good description of a phenomenon that is also affected by other variables not included in the survey.

[Table 3 here]

[Figure 3 here]

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

[Table 4 here]

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

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.

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

Under the conditions covered in this study, being a well-managed standing skyline setup, shock-load events were relatively rare (≤ 10% of the cycles) and weak (max. 30% above SWL). They were weaker but more frequent under the double-hitch treatment, which can readily be explained by the smaller pulling power of the motorized carriage. Under the double-hitch treatment the dropline was powered by a separate 37 kW engine, while under the single-hitch carriage treatment the pull was provided through the mainline and powered by the yarder 175 kW engine. Therefore, while the observed phenomenon was the same - i.e. a very rapid increase of tension followed by a sudden drop and a rest period - the mechanics were different. While in both instances the root cause was the load getting stuck, under the double-hitch treatment the sudden drop arrived earlier and depended on the dropline reaching its maximum pull without being able to break out the load and having to give up; in contrast, under the singlehitch treatment, it was the operator who decided to stop pulling when he realized that he would break the cable or tear down an anchor if he continued. The relatively long lull period after the tension spike derived from the operator changing the hitch or crosscutting the stem to free it from the hang-up. However, even under the more aggressive single-hitch treatment, shock-loads were relatively small and always within the endurance limit (50% of minimum breaking strength: 220 kN in this specific case).

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

The study also produced a regression model for predicting mean skyline tension at midspan as a function of payload size. This model had a strong predictive value as accounted for over 80% of the total variability in the data. As such, it was fit to produce a reliable estimate of mean skyline tension at midspan, where tension was highest. Study data indicated that peak tension at midspan was 2% and 13% higher than mean tension, for the double-hitch and single-hitch treatment, respectively. These were the largest differences recorded in the study, and peak tension exceeded mean tension by 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 installations and configurations, also performed in the same region (Mologni et al. 2019). Taken together, these studies suggest that loggers in the Italian Alps (and possibly in the wider Alpine region) may operate within safe limits of wire rope capability, while occasionally exceeding legal requirements in terms of SWL. In turn, that supports the decision made by the European Standardization Agency (Technical Committee 144, Working Group 8) to decrease the skyline safety factor from 3 to 2.5 for those yarders equipped with a calibrated slip brake on the skyline drum, like the machines included in this and in the 2017 study. Of course, even if the level of overloading applied by the operators in these tests is likely representative of general practice, there will always be the occasional operator who may push the envelope (Marchi et al. 2019; Mologni et al. 2019). In that regard, it is worth recalling that the study was conducted during a salvage operation, where trees had not been felled systematically according to a well-defined plan but had been pushed down over each other and were especially hard to disentangle. Under the conditions of a planned harvest, where trees are felled directionally with a view to facilitating extraction, it is likely that hang-ups would be less frequent and easier to resolve. Therefore, this study 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 factors, provided that operators act responsibly. Of course, all the considerations made above are only valid for standing skyline set ups, and cannot be extended to other configurations without proper validation.

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

If dynamic loading is small and the weaker shock-loads experienced with the double-hitch treatment are not an inherent benefit of the double-hitch working mode, then what are the advantages of double-hitch carriages? This would be summarized as better clearance. Assuming a piece length of 20 m (taller trees are generally crosscut before yarding), double-hitch yarding would offer a clearance gain of approximately 10 m, accounting for a crown radius of ca. 5 m. However, the heavier weight of the carriage would cause an increase in deflection, so some of this gain would be lost. In the 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} can be calculated at 8.4 m and 9.3 m for the single-hitch and the double-hitch carriage, respectively (Worksafe BC 2006). Therefore, changing to double-hitch yarding would increase clearance by ca. 9 m. Whether this benefit is worth the cost depends on the specific set up and corridor; where clearance is not an issue, there is no point introducing a heavier and more expensive double-hitch carriage. Conversely, the advantage can be crucial with specific terrain profiles, and may allow shot-gunning loads downhill where that would not be feasible otherwise. For that reason, double-hitch carriages could represent an especially valuable addition to conventional sled-winch operations, which are still very popular in the Alpine area (Spinelli et al. 2013). Furthermore, double-hitch horizontal suspension would be crucial when extending cable yarding to flat terrain in sensitive sites (Erber and Spinelli 2020). In any case, it is worth noting that double-hitch carriages are designed by fitting a conventional motorized dropline carriage with a dedicated extension: the main investment remains that of the base carriage, which can easily swap configurations, thus adapting to highly variable terrain conditions.

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

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

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Declaration of interest statement

No conflicts of interests to be declared.

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

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

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 cycle includes passing over the intermediate support; Midspan = the cycle includes passing through midspan; No Mid = the cycle does not include passing through midspan; Shock = the cycle includes one shock-load event; No Shock = the cycle does not include any shock-load events;

Table 2. Tension at midspan.

Treatment		Double-hitch				Single-hitch				U-test
		n	**Mean**	**Median**	**Max**	**n**	**Mean**	**Median**	**Max**	**P-Value**
Midspan mean	kN	54	150	150	180	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

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

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

Average tension at midspan

Tension (kN) = a + b * PT + c * Load + d * Double

R^2 adj = 0.827, n = 121, RMSE = 5.867

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

Peak tension at midspan

Tension (kN) = a + b * PT + c * Load + d * Double

R^2 adj = 0.688, n = 150, RMSE = 7.817

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

MCLA at midspan

MCLA (kN) = a + b * Load + c * Double

R^2 adj = 0.303, n = 121, RMSE = 8.596

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

MCLA not at midspan (for cycles through midspan)

MCLA (kN) = a + b * Load + c * Double

R^2 adj = 0.470, n = 61, RMSE = 4.807

	Coeff	**SE**	**T**	**P-Value**
a	14.72	1.55	9.47	<0.0001

Table

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

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

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

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

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

Table 2. Tension at midspan.

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

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).

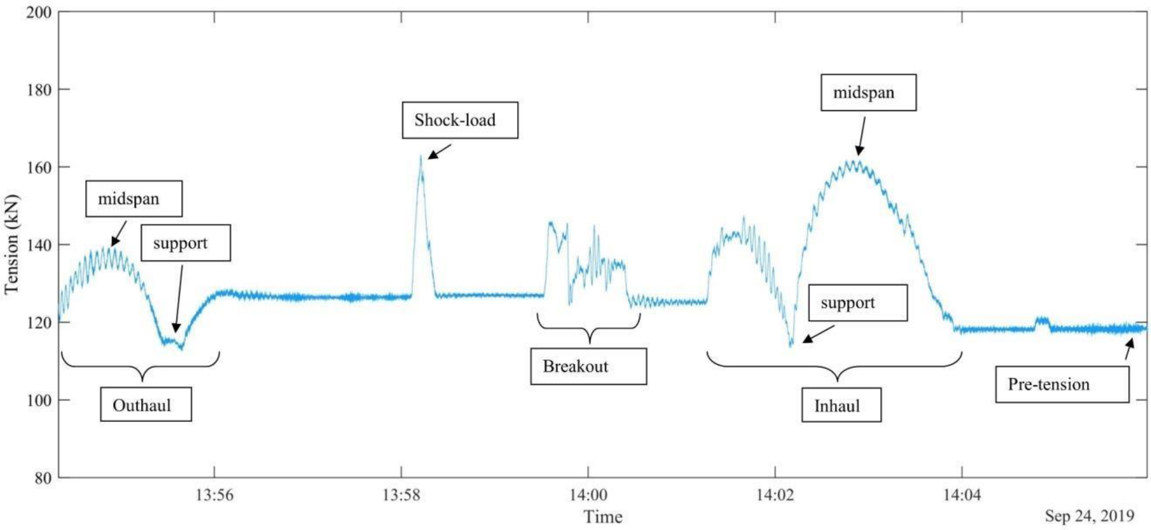

Figure 2. Example of a classic tension graph. Note: time on the x-axis is in the hours:minutes format.

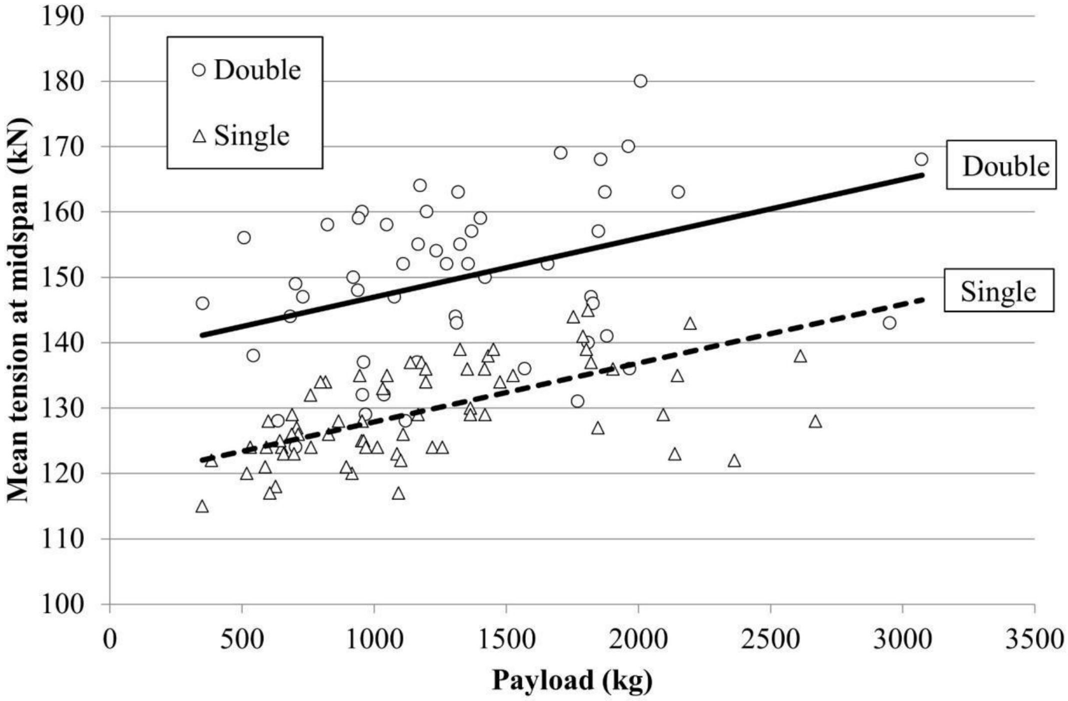

Figure 3. Point scatter and regression graph for mean tension at midspan. The graphs were calculated using the equation in Table 3, for the mean pre-tension of 109 kN for the double-hitch carriage and 103 kN for the single-hitch carriage.

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