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The issue of climbability has been raised on several occasions for more than a decade in North America. Presently, climbability is estimated from the pole hardness measured by the Pilodyn measurements (6 J). However, the use of Pilodyn measurements to discriminate the pole hardness value is criticized by climbers, who claim that the Pilodyn hardness measurement is affected by species-treatment combinations and that it does not reflect gaff penetration or climbability. Furthermore, climbability evaluations have been conducted in which test poles were climbed by linemen, and corresponding subjective ratings were recorded. However, the ability of psychophysical measurements to accurately discriminate close hardness pole values and to differentiate species-treatment combinations at specific hardness levels have not yet been fully documented. The aim of this study is to evaluate the psychophysical perception of linemen and the mechanical measurements of gaff penetration and gaff impact during the climbing of different wood species and treatment combinations in order to compare these results with Pilodyn measurements within a precise range of pole hardnesses, to study the relationships between these variables, and, finally, to propose various design guidelines for the development of a better tool for the evaluation of climbability.

psychophysical measurements   experimental design   wood pole hardness   pole climbability   Pilodyn

1. INTRODUCTION

Wood poles for the transmission and distribution of electrical power and communications are susceptible to decay by organic agents and weather. To prevent deterioration, wood poles are treated with a variety of substances. Traditionally they were treated with oil type wood preservatives such as creosote and pentachlorophenol/oil (PCP/oil). However, the water-borne chromated copper arsenate (CCA) preservative has gained a significant market share, due in part to the negative environmental impact of PCP/oil. With the more extensive use of the CCA preservative, the reported comments of linemen have indicated that CCA-treated poles were excessively hard, which greatly affected their climbability.

To overcome CCA pole hardness, modified formulations have been developed. CCA-PEG, for example, utilizes Polyethylene Glycol as an additive to soften the pole and therefore to provide improved climbability (Messina & Landry, 1986; Trumble & Messina, 1985). Such an additive has shown significant promise in several wood species but its long-term performance has not been sufficiently investigated (Brudermann, 1994; Hanrahan, 1993). A new formulation, CCA-PEG+, has recently been developed (Cooper, Ung, Ma, & Zirk, 1995) and is now being commercially used.

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Relevance to industry: Presently, the ability to safely ascend utility poles is estimated from the Pilodyn measurement. This test basically consists of measuring the penetration of a spring loaded stricker into the pole. The results of our study have revealed a strong interaction between the Pilodyn measurement and the species-treatment combinations, which explains the reason why this measurement does not reflect the pole hardness. The results show that it is necessary to include information concerning the impact generated by the gaff penetration in order to adequately correlate to the perception of hardness. The proposed design guidelines are very important to telephony and electrical companies as they will provide a much more accurate tool to adequately evaluate pole climbability.

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The issue of climbability has been raised on several occasions for more than a decade in North America (Hawthorne, 1981; Sneider, Orr, Martin, & Joy, 1984). It is defined as "the ability to safely ascend a pole and to stand at a working position on a pole using standard spurs" (Brudermann, 1994, p. 4). Climbability is mainly affected by the physical properties of the pole, the climbing tools, and human factors, including the condition and the ability of the climber. Presently, climbability is estimated from the pole hardness measured by the Pilodyn (6 J). The Pilodyn test consists of injecting a spring-loaded (6 joule force) blunt-ended stricker (2.5 mm diameter) into the pole. The penetration depth of the pin is an indication of pole hardness and climbability as it simulates the penetration of a gaff. The deeper the pin penetrates, the easier the gaff penetration is likely to be. However, the use of Pilodyn measurements to discriminate the pole hardness value is criticized by climbers, who claim that the Pilodyn hardness measurement is affected by species-treatment combinations and that it does not reflect gaff penetration or climbability (Ontario Hydro, Bell Northern Research, & Bell Canada, 1982). Furthermore, climbability evaluations have been conducted, in which test poles were climbed by linemen and corresponding subjective ratings were recorded (Messina & Landry, 1986; Ontario Hydro et al., 1982). However, the ability of psychophysical measurements to accurately discriminate close hardness pole values and to differentiate species-treatment combinations at specific hardness levels have not yet been fully documented.

The aim of this study is to evaluate the psychophysical perception of linemen and the mechanical measurements of gaff penetration and gaff impact during the climbing of different wood species and treatment combinations in order to compare these results with Pilodyn measurements within a precise range of pole hardnesses, to study the relationships between these variables, and, finally, to propose various design guidelines for the development of a better tool for the evaluation of climbability.

2. METHODOLOGY

2.1. Pole Selections

The poles selected for this study do not constitute a representative sample of the utility pole population found in the field. The sample has been designed to obtain a uniform Pilodyn penetration distribution ranging from 8 to 14 mm. A pole was selected if the Pilodyn penetration (6 J) measurements taken around and on the length of the pole were statistically homogeneous (24 measurements). At the beginning, we were looking for 6 red pine poles treated with CCA-PEG and 6 yellow pine poles treated with PCP/oil. The poles we could find within a reasonable period of time were all classes 4 and 5 with the characteristics as described in Table 1. The poles obtained with a mean Pilodyn penetration near 14 mm were a red pine treated with CCA-PEG+ and a grey pine treated with PCP/oil.

TABLE 1. Characteristics of the Poles Tested in the Study

Wood Species	Treatment	Pilodyn[1] (mm)	Actual Pilodyn[2]		Density[3] (kg/m^3)	Humidity[4] (average)	Circumference (cm)
			average	*SD*			
Red Pine	CCA-PEG	9	8.4	0.84	593.44	7.42	77.5
Red Pine	CCA-PEG	10	9.6	0.76	655.06	18.31	91.4
Red Pine	CCA-PEG	11	10.8	0.73	604.61	18.81	83.8
Red Pine	CCA-PEG	12	12.2	0.82	551.66	18.05	84.5
Red Pine	CCA-PEG	13	12.8	0.95	655.63	26.25	80.0
Red Pine	CCA-PEG+	14	13.8	1.18	706.47	30.59	106.7
Southern Yellow Pine	PCP/oil	9	9.2	0.97	876.10	19.18	90.8
Southern Yellow Pine	PCP/oil	10	10.2	0.85	897.48	19.15	77.5
Southern Yellow Pine	PCP/oil	11	10.7	0.87	732.85	25.56	105.4
Southern Yellow Pine	PCP/oil	12	11.7	1.42	1087.33	21.16	99.1
Southern Yellow Pine	PCP/oil	13	13.3	0.98	854.92	22.39	99.7
Grey Pine	PCP/oil	14	13.7	0.82	747.48	17.71	86.4

Notes. 1—hardness class based on Pilodyn test readings; 2—average Pilodyn test readings performed before, during, and after the experimental week; 3—average total density (sample not dry) taken around the pole; 4—average humidity measurements performed at three depths (6.4, 12.7, and 29.2 mm) during the entire experimental week.

2.2. Design of Experiment

A full factorial design of the experiment has been selected for the study. It allows the mean Pilodyn penetration effects on psychophysical perceptions, gaff penetration in the wood, and the resulting impact to be studied. The experimental design was a 12 × 2 factorial design; that is, 12 mean Pilodyn penetrations and 2 replicates. In total, 576 experimental trials (12 × 24 participants) were conducted in the study. The linemen who participated in the study were recruited from Bell Canada, Hydro-Québec, and independent hydroelectric companies.

2.3. Dependent Variables

The following dependent variables were measured in the study:

- the linemen's *psychophysical perception* of pole hardness, physical discomfort, and safety perception while climbing the pole, and overall appreciation of the pole. These variables were measured using visual analog scales (VAS) with verbal anchors at the left and right endpoints (for example, "soft" and "hard" anchors for the hardness evaluation);
- *gaff penetration* in the wood pole in the direction of the spur. The variable was measured using a linear voltage displacement transducer (LVDT) that gives a voltage proportional to the displacement. Gaff penetration was recorded at each lineman step;
- the *impact* generated by gaff penetration in the direction of the spur. The impact was measured using an accelerometer.

2.4. Participants

Twenty-four experienced linemen participated in this study. Twelve of them were recruited from Hydro-Québec, 6 were recruited from Bell Canada, and 6 were recruited from independent hydroelectric companies. The linemen had the following characteristics: average age of 37.8 years (SD = 5.9 years), average height of 174.7 cm (SD = 4.9 cm), average weight with equipment of 97.2 kg (SD = 12.2 kg), average pole climbing experience of 13.7 years (SD = 7 years). The linemen were randomly selected. Twelve out of the 24 linemen were required to wear the spur apparatus (Bashlin), which was specially designed to record gaff penetration and gaff impact.

2.5. General Procedure

The experimental trials were conducted in December 1995. Because of the weather conditions at this time of the year (temperature close to −20 °C), the poles were installed inside a large heated tent. The 12 poles were erected in a circle with a span of about 1.5 to 2 m between them. The poles were about 4 m high. In fact, a pre-trial test revealed that the perception of the linemen is similar while climbing poles from 0 to 3 m and from 6 to 9 m.

It took 6 days to complete all the experimentation. There were 4 linemen per day: 2 in the morning and 2 in the afternoon. Two linemen, 1 in the morning and 1 in the afternoon, were instrumented (spur apparatus) as we had only one set of instruments. Figure 1 shows a schematic representation of a typical experimentation day.

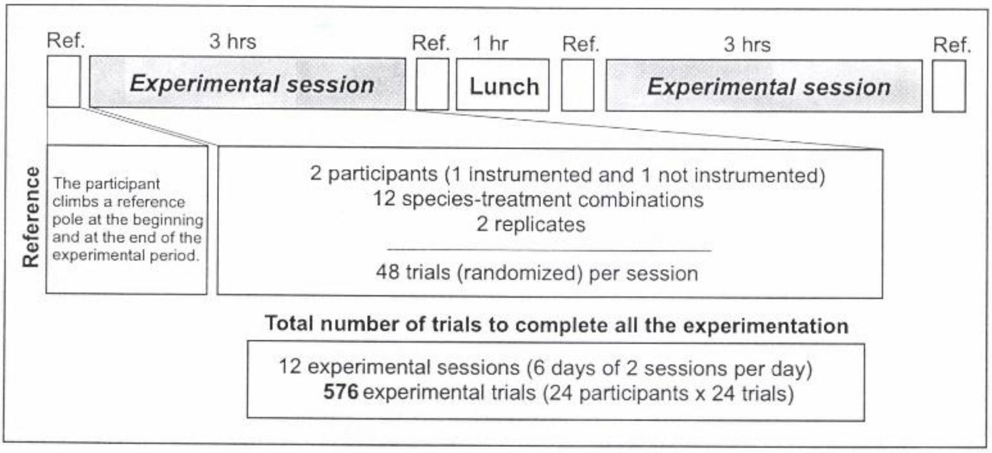

Figure 1. Schematic representation of a typical day of experimentation.

Upon their arrival at the experiment site, each team of 2 linemen was given verbal instructions about the general procedure. They were then required to sign a consent form. A volunteer was asked to wear the spur apparatus.

Before undergoing the experimental trials, each lineman was required to climb a so-called practice pole in order to become familiar with the use of a fall arrest system (Pole Choker Mark 2), which was compulsory for all the linemen. Following this step, each lineman was required to climb a "reference pole" at the beginning and end of a complete experimental session, and to complete the psychophysical scales. These reference trials were used to ensure that the psychophysical perception scores reported by each lineman remained unchanged before and after a complete experimental session. An analysis of variance conducted on all the 24 linemen showed no significant difference in psychophysical scores before and after an experimental session.

After these preliminary steps were completed, the linemen were asked to climb the 12 poles twice. They were also instructed to climb the pole to the top (about 3 m high), then to stretch to their left and right sides in order to simulate an actual reach action, and to climb down the pole. After performing the trial, the linemen were required to complete the psychophysical rating scales. A rest period was provided between each trial. Each trial was repeated one more time, thus leading to the completion of 24 trials per lineman: 12 poles × 2 replicates. The trial order was completely randomized for each lineman. In total, the 24 linemen completed 576 trials during the 6 experiment days.

Penetration and impact measurements were recorded during ascent and descent of the pole. On average, six steps were observed during ascent and four during descent of the pole. In total, 1728 and 1152 penetration measurements were recorded during ascent and descent, respectively.

3. RESULTS

Analyses of variance (ANOVA) were applied to all the experimental data collected in this study (Montgomery, 1994). The following dependent variables were studied:

- psychophysical perception: pole hardness, physical discomfort, safety perception, and overall pole appreciation;
- physical measurements: gaff penetration during ascent and during descent, impact during ascent and during descent.

The .05 significance level ($p < .05$) was adopted in the evaluation of all effects.

3.1. Psychophysical Evaluation

In this paper, only the linemen's perception of hardness is presented. All other results were similar. An analysis of variance, taking into account the mean Pilodyn penetration variables, was applied to the linemen's perception of hardness data. The ANOVA result is presented in Table 2.

TABLE 2. ANOVA Table for the Linemen's Perception of Hardness

Source of Variation	*df*	*SS*	*MS*	*F*	*p* <
Linemen	23	65440.80	2845.30		
Pilodyn penetration (P)	11	170101.00	15463.70	33.41	0.0000
Replicate (R)	1	146.50	146.50	0.43	0.5257
P × R	11	1299.01	118.09	0.60	0.8255
Error	253	49527.70	195.76		
Total	575	411457.00			

After the data were analyzed, we then applied the Newman-Keuls test (multiple comparison test) to the dependent variable. This test allows further examination of the difference between the various Pilodyn penetrations. The test results are shown in Figure 2, where different letters reveal significant differences between Pilodyn penetrations ($p < .05$). The 95% confidence limits on the mean are also displayed for the dependent variable (vertical axis) as well as the Pilodyn measurements collected before, in the middle, and at the end of the experimental week (horizontal axis).

Figure 2 reveals that at an equivalent Pilodyn penetration, the linemen's perceptions of hardness between the two species-treatment combinations is not constant, thus suggesting an interaction effect between species-treatment combinations and mean Pilodyn penetrations. This figure also reveals that yellow pine poles treated with PCP/oil are perceived as less "hard" by linemen than red pine poles treated with CCA-PEG at equivalent mean Pilodyn penetrations. Furthermore, it is also interesting to note that linemen can better discriminate the mean Pilodyn penetration of red pine poles treated with CCA-PEG. An examination of the relative positions of the two species-treatment combinations clearly suggests that a Pilodyn measurement alone does not reflect the linemen's perception of hardness if we do not distinguish between species-treatment combinations. However, there is a clear relationship between the linemen's perception of hardness and the mean Pilodyn penetration within each species-treatment combination. This relationship is more noticeable for the red pine and CCA-PEG combination.

Figure 2 also shows that the linemen's perception of hardness of the red pine pole (CCA-PEG) with a mean Pilodyn penetration of 12.8 mm is equivalent to those of the yellow pine poles (PCP/oil) with mean Pilodyn penetrations of 9.2, 10.2, and 10.7 mm. Finally, the three poles

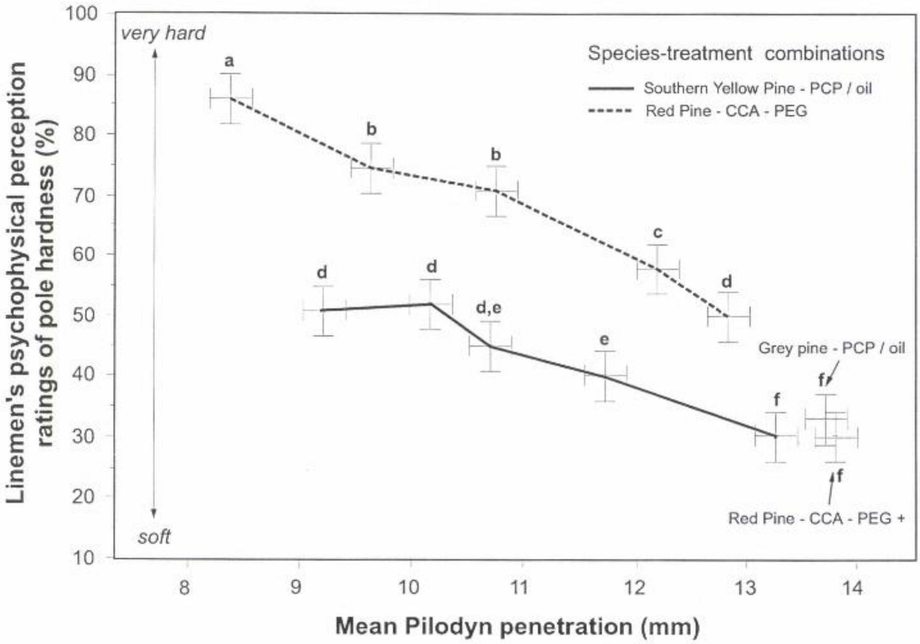

Figure 2. Linemen's psychophysical perception of hardness as a function of mean Pilodyn penetration.

with a mean Pilodyn penetration greater than 13 mm show an equivalent linemen's perception of hardness.

Pole Acceptability

At the end of each experimental session, we asked each lineman to give his overall appreciation of each of the 12 poles. To conduct this last evaluation, each lineman was required to climb each pole again and to determine whether the pole is acceptable or unacceptable. Figure 3 presents the results of this evaluation. The percentage acceptability of each pole represents the proportion of the 24 linemen that has accepted the pole. Furthermore, Figure 4 shows the results of a cluster analysis conducted on the data collected in this evaluation. This analysis leads to the determination of five classes of poles.

From Figure 3 it can be seen that the linemen accepted the yellow pine poles treated with PCP/oil (including the grey pine pole) in a larger proportion than the red pine poles treated with CCA-PEG (with the exception of the red pine pole treated with CCA-PEG).

Furthermore, it is also interesting to note that the red pine pole with a mean Pilodyn penetration of 12.8 mm shows a percentage acceptability equivalent to or greater than the yellow pine poles (PCP/oil) with a mean Pilodyn penetration less than 12 mm, the latter being harder from a Pilodyn standpoint.

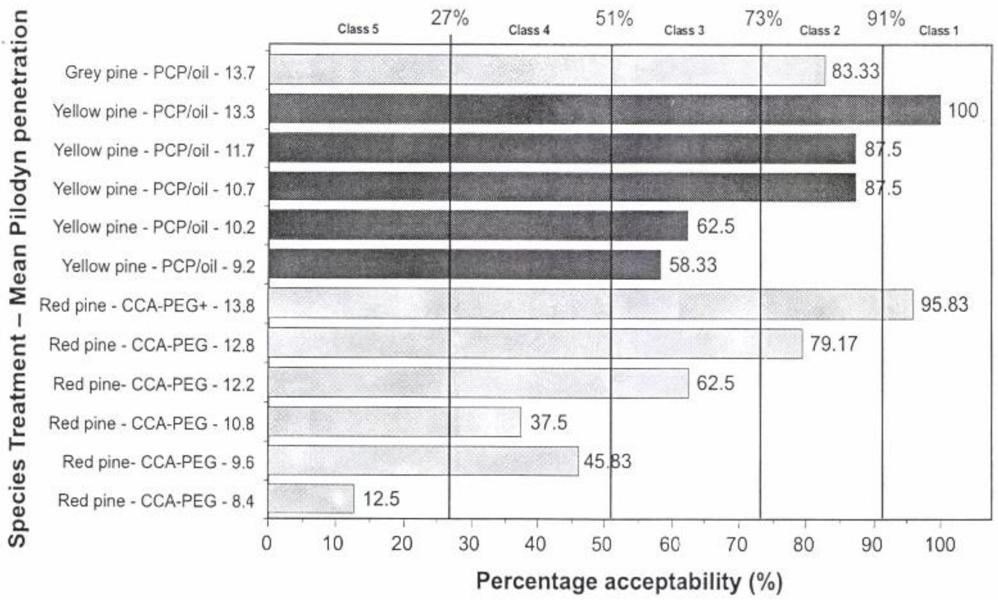

Figure 3. Percentage acceptability of poles as a function of species-treatment combinations and mean Pilodyn penetrations.

TABLE 3. Classification of Poles as a Function of Percentage Acceptability

Class	PCP/oil	CCA-PEG (PEG+)	Acceptability	Average
1	13.3	13.8 (PEG+)	> 91%	98%
2	10.7, 11.7, 13.7 (grey pine)	12.8	73–91%	84%
3	9.2, 10.2	12.2	51–73%	61%
4		9.6, 10.8	27–51%	42%
5		8.4	< 27%	12.5%

Notes. CCA—chromated copper arsenate, PEG—polyethylene glycol, PCP—pentachlorophenol.

Starting with Figures 3 and 4, it is then possible to classify the poles as represented in Table 3.

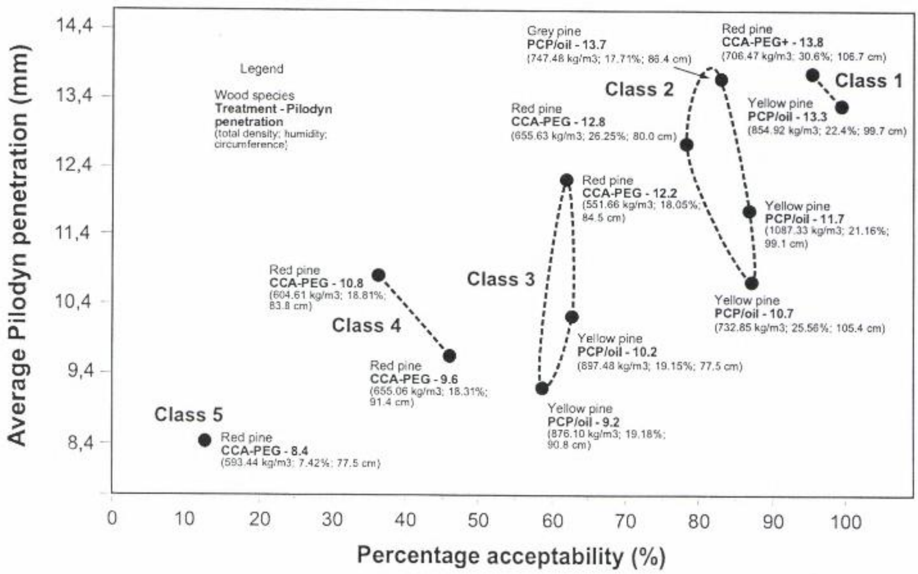

Figure 4. Classification of poles as a function of percentage acceptability.

3.2. Physical Measurements

Figures 5 and 6 show an example of gaff penetration and impact measurement. Two impacts occur during gaff penetration, one at the beginning of the penetration and the other at the end of the course (see

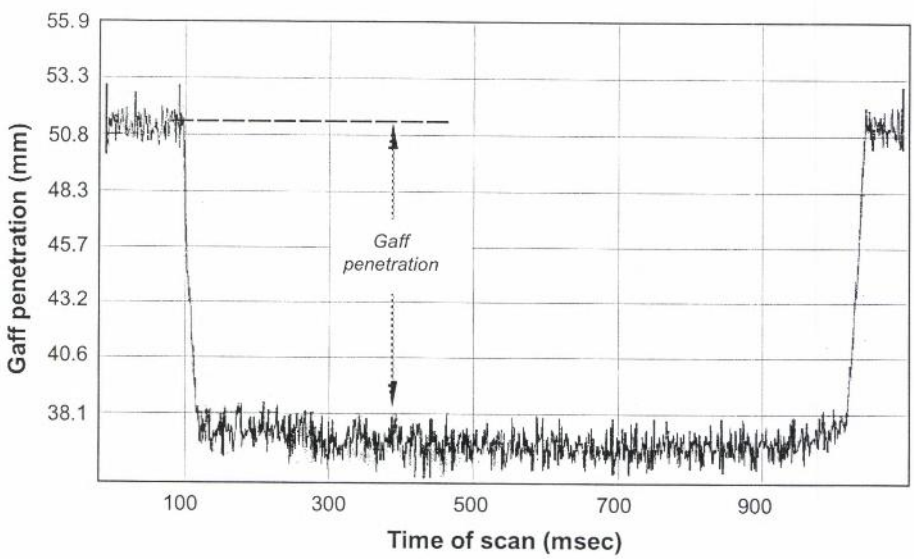

Figure 5. Example of a gaff penetration measurement.

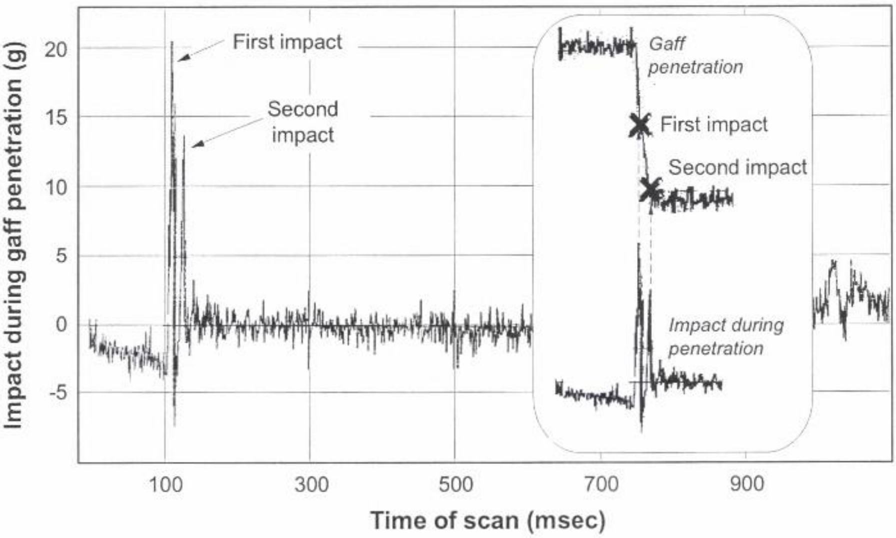

Figure 6. Example of an impact during gaff penetration.

Figure 6 for the exact location of impact during gaff penetration). Only the first impact was considered in the analysis. Analyzed data are based on a mean of six penetrations during ascent and four penetrations during descent. Only the descent results are presented in this paper.

Analysis of variance (ANOVA) was applied to the collected data to investigate the main effect of mean Pilodyn penetrations on gaff penetration and impact during descent of the pole.

3.2.1. Gaff penetration during descent

Table 4 presents the results of ANOVA applied to the gaff penetration data collected during descent. The results reveal a significant Pilodyn penetration effect on gaff penetration ($p < .0001$).

TABLE 4. ANOVA Table for Gaff Penetrations During Descent

Source of Variation	*df*	*SS*	*MS*	*F*	*p* <
Linemen	11	4.74141000	0.43103700		
Pilodyn penetration (P)	11	6.16513000	0.56046700	44.96	0.0000
Replicate (R)	1	0.00367869	0.00367869	0.20	0.6690
P × R	11	0.14805100	0.01345920	1.44	0.1643
Error	119	1.11283000	0.00935153		
Total	285	13.83550000			

Figure 7 shows the effect of the Pilodyn penetration variable on the dependent variable. This figure reveals that gaff penetration increases (in general) with Pilodyn penetration. There is also a clear difference between the two species-treatment combinations. In general, the yellow pine poles treated with PCP/oil give a greater gaff penetration than the red pine poles treated with CCA-PEG. The gaff penetrations of red pine poles with a mean Pilodyn penetration varying from 9.6 to 12.2 mm are equivalent. This can be explained by the fact that the linemen perform positive mechanical work during descent and that they reach the maximum penetration, particularly with the red pine poles (CCA-PEG), with a Pilodyn penetration between 9.6 and 12.2 mm. These poles, furthermore, are equivalent to the yellow pine pole (PCP/oil) with a Pilodyn penetration of 9.2 mm. The maximal penetration varied from 14.5 to 29.5 mm for the red pine poles (CCA-PEG and CCA-PEG+), and from 18.5 to 23.9 mm for the yellow pine poles treated with PCP/oil. If we consider the projection of the penetration variations as a function of the gaff angle from the perpendicular plane to the pole surface, then it is quite unlikely that these results were affected by the variation in humidity inside the wood. Finally, the largest gaff penetration was observed with the red pine pole treated with CCA-PEG+.

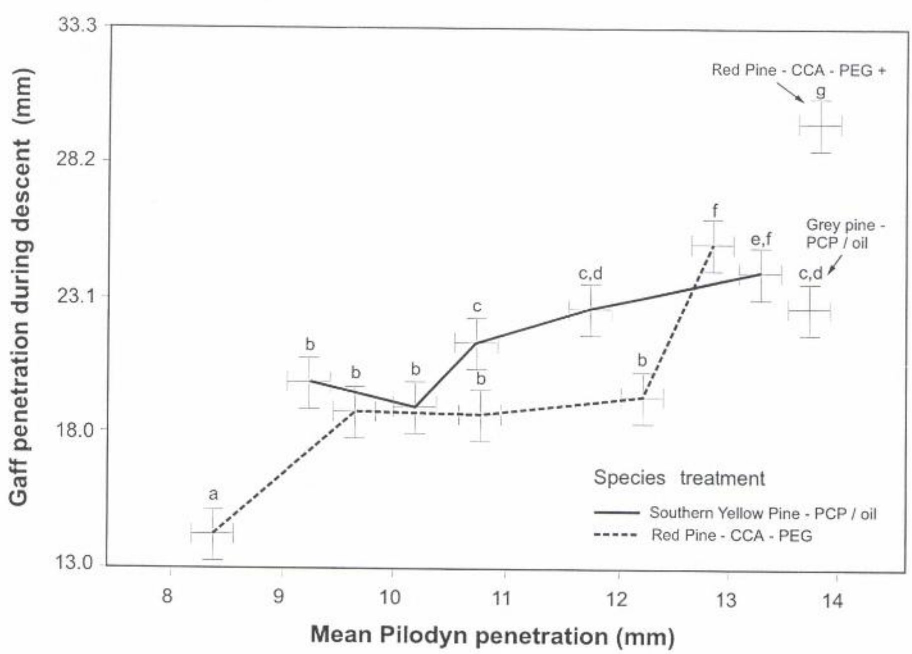

Figure 7. Gaff penetration during descent as a function of mean Pilodyn penetration.

3.2.2. Impact during gaff penetration during descent

Table 5 presents the results of ANOVA applied to the impact data collected during descent. The results reveal a significant Pilodyn penetration effect on gaff penetration ($p < .0001$).

TABLE 5. ANOVA Table for Impact During Gaff Penetration During Descent

Source of Variation	*df*	*SS*	*MS*	*F*	*p* <
Linemen	11	4191.2900	381.02700		
Pilodyn penetration (P)	11	1351.2900	122.84500	7.28	0.0000
Replicate (R)	1	27.2223	27.22230	2.86	0.1191
P × R	11	78.8191	7.16537	0.57	0.8515
Error	120	1513.8100	12.61510		
Total	286	9312.0600			

Figure 8 shows the acceleration values (g) as a function of Pilodyn penetration. The impact measured during descent is less than the one measured during ascent (results not shown) because of the greater

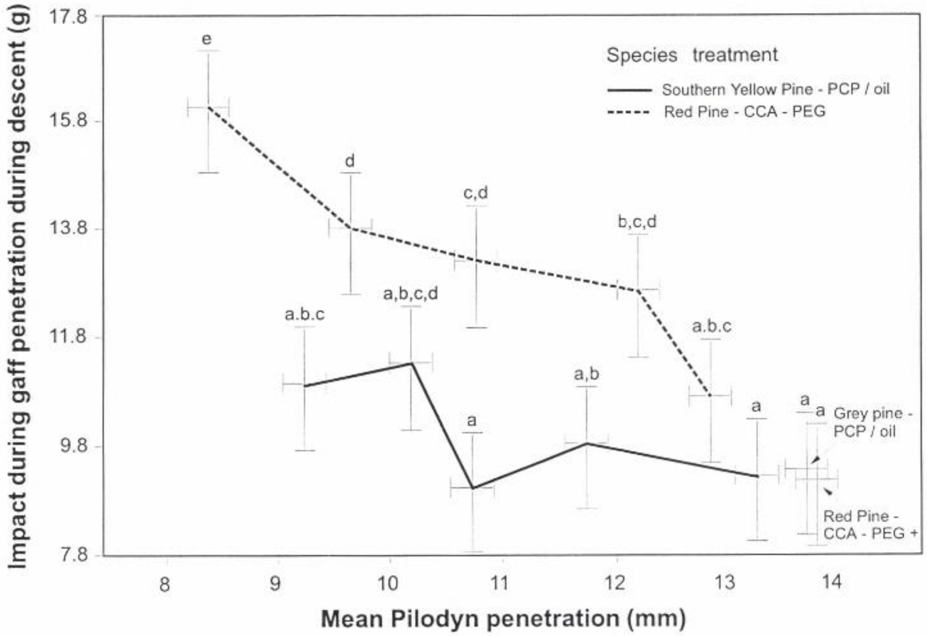

Figure 8. Impact during gaff penetration during descent as a function of mean Pilodyn penetration.

penetration of the gaff during descent. We also observe more significant impact variations with the red pine poles treated with CCA-PEG (from 9 to 16 g). All yellow pine poles (PCP/oil), however, show equivalent impact levels.

4. COMPARISON OF PSYCHOPHYSICAL AND PHYSICAL RESULTS

In order to adequately compare the psychophysical results to the physical results, only the psychophysical data generated by the 12 instrumented linemen were analyzed.

Figure 9 shows a graphical comparison of the linemen's perception of hardness (a) and the impact during gaff penetration (b) as a function of the mean Pilodyn penetration. From this figure it can be observed that the impact during gaff penetration during descent does reflect the linemen's perception of hardness, as a perceived hardness level can be attributed to an impact level. The average impacts vary from 9 to 16 g whereas the linemen's perception of hardness varies from 35 to 85% for the red pine poles treated with CCA-PEG. With the yellow pine poles (PCP/oil), the average impacts vary from 9 to 11.5 g whereas the linemen's perception of hardness varies from 25 to 50%. Figure 10 shows the impact during penetration during descent as a function of the linemen's perception of hardness. Linear regression is applied to the average impact and the linemen's perception results for each Pilodyn penetration level. The analysis leads to a coefficient of determination of 95%. A strong correlation can be observed between impact during gaff penetration during descent and the linemen's perception of hardness.

The previous results revealed that the linemen's perception of hardness is strongly correlated with the impact during gaff penetration during descent. In fact, the coefficient of determination is 95%, that is, the simple linear model describing the relationship between the linemen's perception and the impact explains 95% of the total variability of the mean Pilodyn penetration measurements. The other psychophysical variables, not presented in this paper, have also shown high coefficients of determination ($R^2 > 90\%$). With the four psychophysical variables measured, the highest correlation was always found with the impact during gaff penetration during descent.

In conclusion, these results reveal that it is now possible to obtain an objective indicator that reflects the linemen's perception of hardness based on the amount of impact during gaff penetration during descent. If we compare the results obtained with the pole acceptability evaluations (Figure 3) to those of the impact during gaff penetration during descent (Figure 8), then we can derive a relationship between the impact during

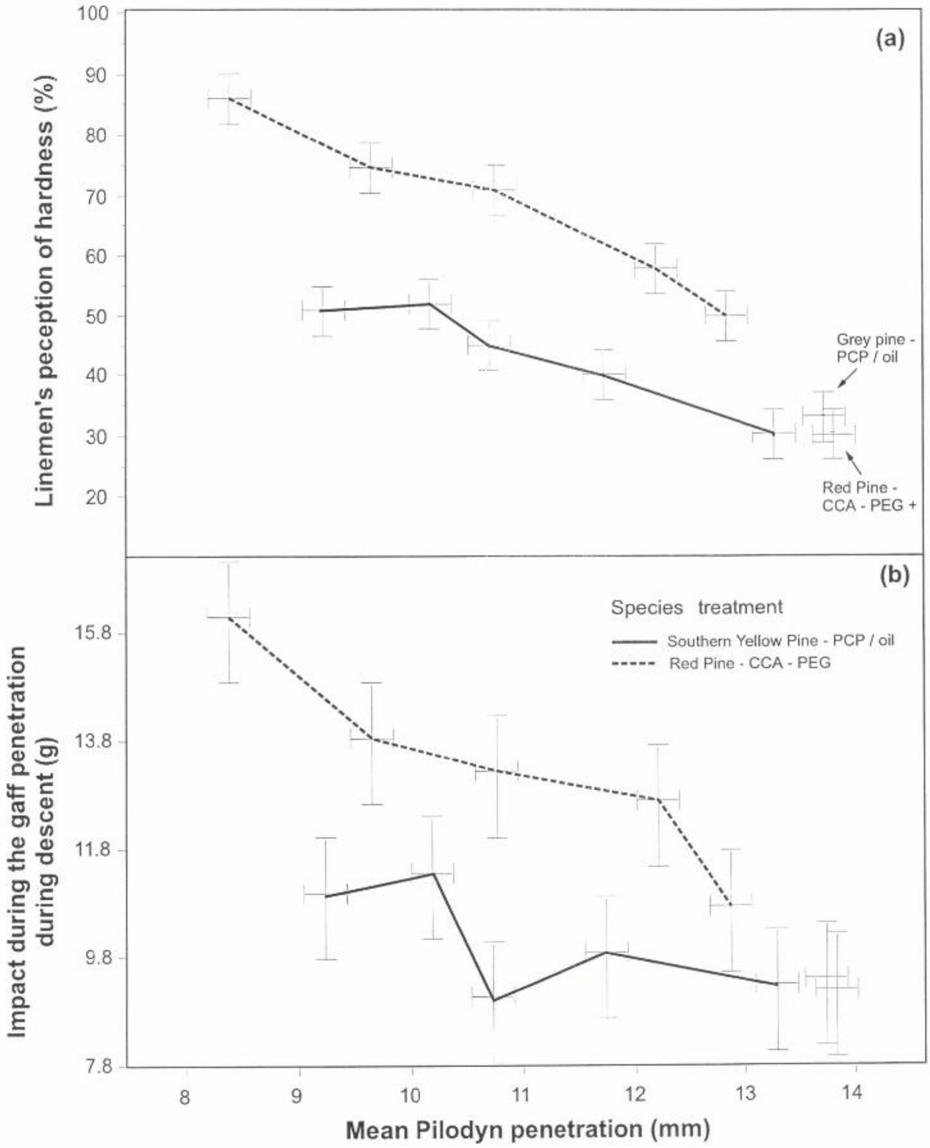

Figure 9. Linemen's perception of hardness (a) and impact during gaff penetration during descent (b) as a function of mean Pilodyn penetration.

gaff penetration during descent and the acceptability rates of poles, independent of the species-treatment combinations. Based upon the five classes defined by the cluster analysis of the acceptability rate (Figure 4), we can define the following four classes of poles:

- Class 1—fully acceptable poles with an acceptability rate greater than 91%;
- Class 2—averagely acceptable poles with an acceptability rate between 73 and 91%;
- Class 3—fairly acceptable poles with an acceptability rate between 51 and 73%;
- Classes 4 and 5—unacceptable poles with an acceptability rate smaller than 51%.

A linear regression analysis applied to the acceptability rate and the impact during gaff penetration during descent has shown a coefficient of determination of 99%. The regression result along with the four classes just defined are presented in Figure 11. A more detailed analysis, based on the regression analyses of both impacts during gaff penetration during descent and ascent (not presented in this paper), allows an impact limit to be defined for each of the four classes (Table 6). As the impact limits are slightly different during descent and ascent, we have applied a "safety" impact limit criterion, that is, the maximum impact level value for class 4 and the minimum impact level value for class 1.

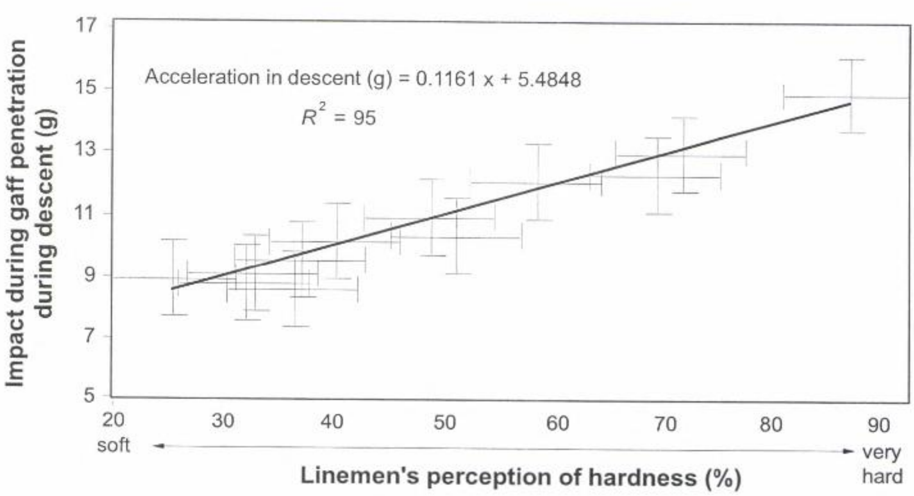

Figure 10. Impact during gaff penetration during descent as a function of linemen's perception of hardness.

This approach leads to an uncertainty zone between classes 2 and 3 for impact values ranging from 11 to 12 g. This uncertainty level represents an acceptability rate of 73%.

The four classes previously defined were combined with the results of gaff penetration during descent and during ascent. This procedure

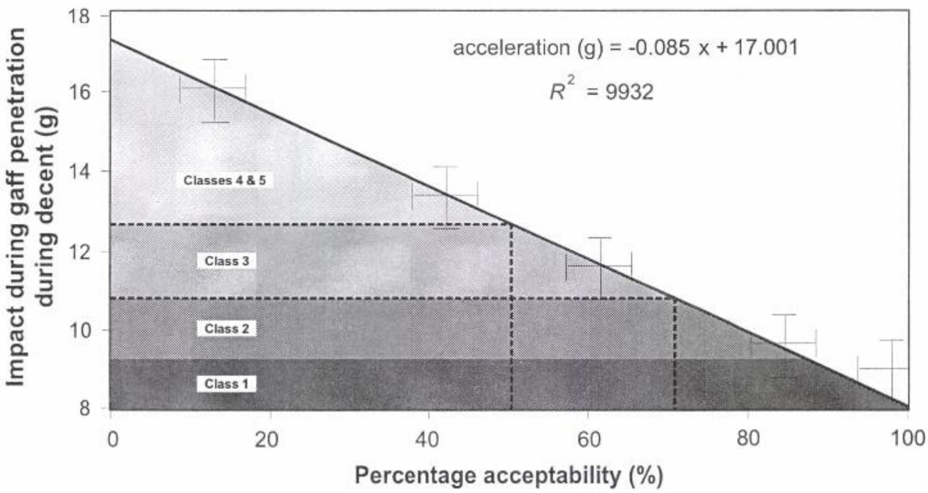

Figure 11. Impact during gaff penetration as a function of the percentage acceptability.

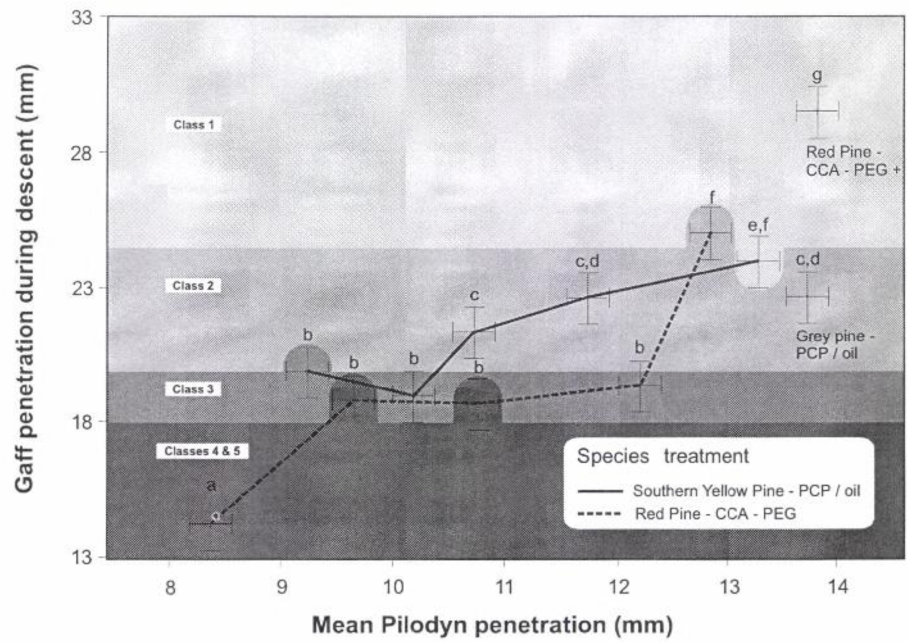

Figure 12. Gaff penetration during descent as a function of mean Pilodyn penetration.

TABLE 6. Table of the Pole's Acceptability Zones as a Function of Linemen's Perception of Acceptability, Impact, Gaff Penetration, and a Severity Index

Poles	Percentage of Rejection by Linemen (%)		Impact Level (g)	Penetration Level (mm)	Severity Index $\frac{\text{Penetration}_{ascent} + \text{Penetration}_{descent}}{\text{Impact}_{ascent} + \text{Impact}_{descent}}$
	Range	Mean			
Fully acceptable	0– 9	2	< 9	> 24	> 2.25
Averagely acceptable	9–27	16	9–12	18–24	1.75–2.25
Fairly acceptable	27–49	39	11–14	16–20	1.4–1.75
Unacceptable	> 49	68	> 14	< 16	< 1.4

allows the pole's acceptability zones to be defined in relation to the gaff penetration measurements (Table 6). The gaff penetrations are obviously different during ascent and during descent, thus leading to uncertainty zones between gaff penetrations of 18 and 22 mm for classes 2 and 3 (Figure 12). This uncertainty level also represents an acceptability rate of 73%. The end zones have been defined according to a safety criterion for penetration.

In order to be categorized in one of the four classes defined in Table 6, a pole must meet both impact and penetration criteria; otherwise the pole falls into a lower class. Furthermore, in order to meet both criteria at the same time, a severity index is defined based on the ratio of the average of the penetration during ascent and during descent over the average of the impact during ascent and during descent (mm/g). This index is described in Figure 13 and is also presented in the last column in Table 6. The results show that all southern yellow pine poles (PCP/oil) can be classified as fully acceptable, whereas the red pine poles (CCA-PEG) must have a mean Pilodyn penetration of 12.2 mm in order to be classified in the same category. In Figure 13, it is important to note that the minimum and the maximum values on the y axis

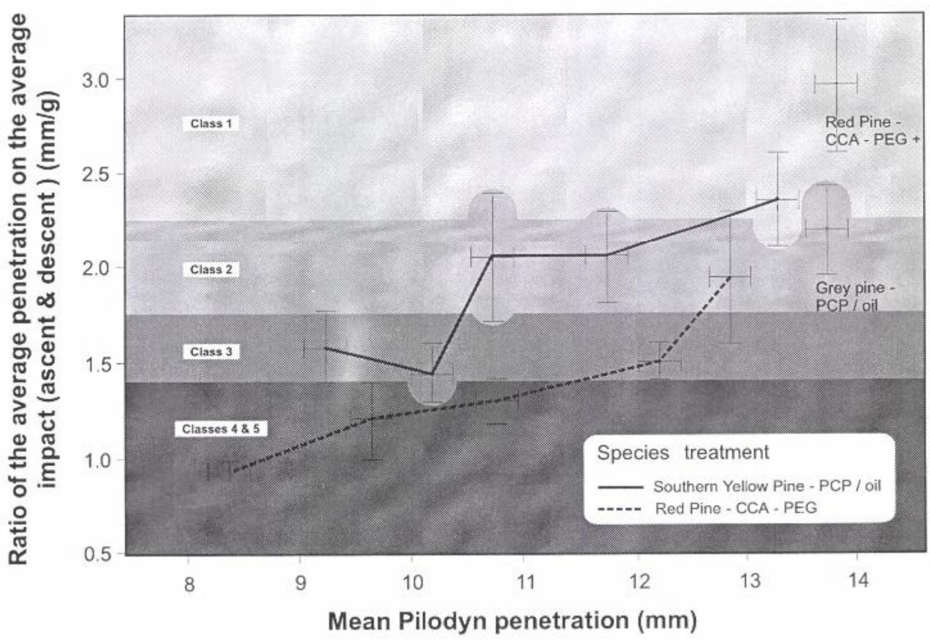

Figure 13. Ratio of the average gaff penetration over the average impact as a function of mean Pilodyn penetration.

correspond to the ascent and the descent values, respectively. These values can be used by managers as a decision criterion for evaluating the climbability of a pole at a specific time. It is important to note, however, that these criteria have been established in a restricted range of Pilodyn penetrations with poles in good condition and with a Bashlin type of gaff. Therefore, any new measuring instrument would need to take into account these study conditions. Furthermore, we offer managers the possibility of defining their own threshold for pole acceptability (acceptability threshold defined in this study is 50%).

5. DISCUSSION

5.1. Psychophysical Evaluations

The analyses of the different psychophysical variables have revealed the same tendency. Although we have focused instead on the linemen's perception of hardness in this paper, the other variables have shown the same effect on the Pilodyn penetration variable.

Although the study has dealt with Pilodyn penetration as the main independent variable, species treatment and the Pilodyn penetration interaction effect, however, have undeniably stood out and the first conclusion is the fact that Pilodyn penetration cannot be used as a discriminating parameter without considering the effect of the species-treatment combination. In fact, the initial research protocol was designed with the wood species, the type of wood treatment, and Pilodyn penetration as independent variables. Such a design, one must say, would have been difficult, considering the poles available in the field. Nevertheless, the results obtained in this study lead to quite interesting findings. The fact that Pilodyn penetration does not reflect the linemen's perception of hardness is not surprising. After all it was the goal of our study.

In particular, linemen more precisely discriminate red pine poles treated with CCA-PEG with a psychophysical rating difference of 10% per millimeter of Pilodyn penetration than they do southern yellow poles treated with PCP/oil with a rating difference of 3% per millimeter of Pilodyn penetration. The results have shown that the red pine poles (CCA-PEG), in general, were perceived as less acceptable than the yellow pine poles (PCP/oil), as a red pine pole required a Pilodyn penetration of 12.8 mm for this species-treatment combination to be perceived as equivalent to yellow pine poles (PCP/oil) with a Pilodyn penetration of 9.2 to 10.7 mm. The poles that were perceived as the most acceptable had Pilodyn penetrations greater than 13 mm, independent of the species-treatment combination. It is important to note that the red pine pole in this category was treated with CCA-PEG+ preservative, and that the pole that was perceived as the least acceptable among those with a Pilodyn penetration greater than 13 mm was a grey pine pole. Although these are rather fragmentary results, they may suggest a possible interaction between species and treatment variables.

It is also important to note that the southern yellow pine poles (PCP/oil) have a higher density than the other poles, thus suggesting that density plays an important role in the linemen's perception of acceptability. The poles' humidity, however, did not show up as a discriminating variable.

From an evaluation based on the amount (percentage) of linemen who found each pole acceptable, the poles have been classified into five classes. From these results, we defined four pole acceptability classes.

- Class 1—fully acceptable poles with an acceptability rate greater than 91%;
- Class 2—averagely acceptable poles with an acceptability rate between 73 and 91%;
- Class 3—fairly acceptable poles with an acceptability rate between 51 and 73%;
- Classes 4 and 5—unacceptable poles with an acceptability rate smaller than 51%.

5.2. Physical Measurements

Almost the same observations made with the psychophysical variables can be applied to the physical variables.

It has been shown that Pilodyn penetration reflects neither the impact during gaff penetration nor gaff penetration with the species-treatment combinations confounded. When we consider each species-treatment combination separately, however, it is then possible to establish a relationship between gaff penetration or the impact during gaff penetration and Pilodyn penetration.

The southern yellow pine poles (PCP/oil), in general, showed deeper gaff penetrations than the red pine poles (CCA-PEG) with the exception of the red pine pole treated with CCA-PEG+, which showed more interesting results in this regard. The southern yellow pine poles (PCP/oil) also showed, in general, less significant impacts during gaff penetration during ascent or during descent. This measurement of the impact is clearly more discriminating for the red pine poles (CCA-PEG) than the southern yellow pine poles (PCP/oil). This latter group of poles (yellow pine poles) presents impact levels that are almost equivalent to all Pilodyn penetrations.

5.3. Relationships Between Psychophysical and Physical Measurements

The results have shown that a clear relationship exists between the results obtained from both the psychophysical and physical evaluations.

The most significant correlation was found in the relationship between the impact during gaff penetration during descent and the linemen's perception variables, with a coefficient of determination reaching 95%.

Particularly, the relationship between the impact measurements during ascent and during descent was established with the pole acceptability rate. From the analysis, poles with an impact of less than 9 g have been established as fully acceptable and poles with an impact greater than 14 g have been defined as unacceptable. Poles with an impact value that falls into the ranges from 9 to 11 g and from 12 to 14 g have been considered as average and fairly acceptable, respectively. An uncertainty zone within the range of 11 to 12 g subsisted between the poles classified as fair and average.

The relationship between the pole acceptability rate and gaff penetration during descent and during ascent has established that poles with a gaff penetration greater than 24 mm were fully acceptable, and that poles with a gaff penetration of less than 16 mm were considered as unacceptable. Poles with a gaff penetration within the range of 20 to 24 mm could be classified as average, whereas poles with a gaff penetration within the range of 16 to 18 mm could be classified as fair. Again, an uncertainty zone within the range of 18 to 20 mm still subsisted between the poles classified as fair and average.

Furthermore, we have developed a severity index based on the ratio of the average gaff penetration during ascent and during descent divided by the average impact during ascent and during descent. From this index, a pole is considered acceptable by more than 50% of the linemen when the severity index is higher than 1.4 mm/g ($\pm$ 0.2 mm/g).

These results could be applied as decision criteria by the managers.

6. CONCLUSION

The aim of this study was to investigate the relationships between various psychophysical variables, such as perception of hardness, physical discomfort, safety perception while climbing a pole, and the overall appreciation of the pole with the Pilodyn penetration. In order to gain detailed knowledge about these relationships, we have also introduced pertinent physical variables into the experimental protocol, such as impacts during gaff penetration during both ascent and descent, and gaff penetrations into the wood pole during both ascent and descent. The specific objective we pursued by introducing these physical measurements was to eventually define a key indicator that could be used to evaluate the climbability of treated wood poles.

The study was conducted with a set of 12 poles selected on the basis of pre-defined Pilodyn penetration values to uniformly cover a restricted range of Pilodyn penetrations (from 9 to 14 mm) for two species-treatment combinations, that is, a combination of red pine poles treated with CCA-PEG and another combination of southern yellow pine poles treated with PCP/oil. It is well understood that these samples did not reflect the actual treated wood poles in the field, but did allow us to obtain poles with Pilodyn penetrations within the desired range of penetrations. The methodology used is based on a completely randomized-within-participant experimental design, by which the effect of the Pilodyn penetration variable over a set of dependent variables can be studied. The data analyses (576 experimental data for each of the psychophysical variables analyses and 286 experimental data for each of the physical variables analyses) were conducted using various analyses of variances, multiple-range test, linear regression, and correlation analyses.

The main results revealed by this study are as follows:

- First of all, it has been determined that Pilodyn penetration does not constitute an effective measurement of pole hardness as it is sensitive to the species-treatment combination. The results have revealed, however, that this measurement can be used effectively for any specific species-treatment combination. This last statement may explain why the criticism of the use of Pilodyn penetration has never been unanimous.
- Another important result revealed by the study is the existence of an interaction between Pilodyn penetration and the species-treatment combinations. In fact, the psychophysical rating difference is not the same from one species treatment to the other, with all the psychophysical variables measured. For instance, the combination of red pine

and CCA-PEG has shown a greater psychophysical rating difference than the combination of southern yellow pine and PCP/oil. These results reveal that an experimental design with wood species, treatment type, and Pilodyn penetration as distinctive independent variables would have provided more complete results on this aspect. Unfortunately, such a design is difficult to achieve due to the difficulty, if not the impossibility, of obtaining the appropriate experimental combinations between these three independent variables (e.g., red pine and PCP/oil with a Pilodyn penetration of 9 mm; or southern yellow pine and CCA-PEG with a Pilodyn penetration of 14 mm).

- More specifically, red pine poles treated with CCA-PEG are in general perceived as less acceptable by the linemen than southern yellow pine poles treated with PCP/oil. These results have been confirmed by the physical measurements as the red pine poles (CCA-PEG) showed a shorter gaff penetration and a greater impact than the southern yellow pine poles (PCP/oil). These results may in part be explained by density differences between the red pine poles and the yellow pine poles, the latter having a greater density. This hypothesis, however, would need to be further evaluated. The results of the psychophysical evaluations have shown that a red pine pole (CCA-PEG) should have a Pilodyn penetration of 12.8 mm in order to be perceived as equivalent to southern yellow pine poles (PCP/oil) with Pilodyn penetrations of 9.2 to 10.7 mm. One should also note that a red pine pole (CCA-PEG+) with a Pilodyn penetration of 13.8 mm has shown results that are equivalent, if not superior, to the southern yellow pine poles tested (PCP/oil) from both the psychophysical and physical standpoints.
- Another important result of this study is the excellent correlation found between the psychophysical measurements, regardless of which psychophysical variables are used, and the physical measurements of both gaff penetration and impact during gaff penetration. These correlations are more significant with the impact measured during descent. In fact, we found coefficients of determination up to 95%. Therefore, any future study on the same problem could be based on a simple psychophysical evaluation of pole acceptability by linemen.
- From the linemen's evaluation of pole acceptability, we have also established four classes of poles: poles fully acceptable with an acceptability rate greater than 91%; poles that are unacceptable with an acceptability rate smaller than 51%; "average" poles with an acceptability rate between 73 and 91%, and "fair" poles with an acceptability rate between 51 and 73%.

- The results have also allowed the permissible levels for impact and gaff penetration to be defined for each of the four classes of poles. These decision criteria for evaluating the climbability of treated wood poles are quite useful to both managers and instrument designers. It is important to note, however, that the gaff penetration criterion must be considered with a spur penetration angle of 23°. In fact, Rey-Lescure and Thomas (1987) have shown in an experimental study that the penetration angle of the spur should be greater than 15° for the climbing operation to be considered safe from an unhooking point of view. They have also shown that a reduction in the angle of penetration leads to an increase in the depth of penetration without necessarily increasing the unhooking resistance. These results suggest that the depth of penetration does not constitute by itself a safety criterion unless the angle of penetration is also considered.
- The limit criteria for impact and gaff penetration cannot be considered separately. Also, if a pole respects only one of these criteria, it must fall into a lower acceptability class. For this purpose, we have proposed a severity index. This index offers the advantage of taking into account both the impact and the gaff penetration values. Finally, we offer the manager the possibility of defining his or her own pole acceptability threshold based on the percentage acceptability by linemen (in this study, acceptability threshold $\approx$ 50%).
- Finally, the results suggest that the climbability threshold for a red pine pole treated with CCA-PEG should be greater than 10.8 mm (fair class and higher) based on a Pilodyn instrument (6 J). At this point, we should recall a study conducted by Ontario Hydro (Hanrahan, 1993), in which the authors reported that a red pine pole (CCA-PEG) with a mean Pilodyn penetration of 9.6 mm was rejected by all the linemen. We should also mention that our climbability threshold is based on an acceptability rate of 51% as reported by the linemen and that it does not correspond to the risk to which the linemen are exposed during climbing activities. Furthermore, all the southern yellow pine poles tested with a Pilodyn penetration greater than 9.2 mm are acceptable. As the climbability threshold is different from one species-treatment combination to another, these partial results would have to be completed, in the case where Pilodyn penetration remains the selection criterion, by a psychophysical evaluation of pole acceptability by linemen on a larger sample of poles in order to define the Pilodyn penetration limits for other species-treatment combinations.

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