Assessing Effects of Environmental Factors on Physical Workload during Motor-manual Timber Harvesting using Motion Capturing Data and Biomechanical Modeling

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Abstract

Forestry workers are at significant risk to suffer from work-related musculoskeletal disorders (WMSD). Challenging environmental factors of the forest can have a significant impact on physical workload of motor-manual timber harvesting, which is already considered highly physical work. Conventional observation methods of risk assessment may underestimate specific environmental factors that influence forestry work. In order to determine whether such factors can increase the risk of WMSD and should therefore be integrated into standard risk assessment methods, a field study was conducted with N=10 forestry workers. The effects of environmental factors on physical workload were analyzed using motion capturing, force measures and biomechanical parameters for the activity of manually pulling a steel cable from a skidder winch over a distance of 20 meters in the forest. Type of execution, ground condition and soil slope as environmental factors were varied to investigate their effects on biomechanical parameters. Compressive force and shear force on the L5/S1 disc were calculated using a biomechanical approach. The results indicated that mean compressive and mean shear forces differed significantly depending on the environmental factors type of execution and soil slope. No significant influence of the factor ground condition was found. The combination of all environmental factors showed a significant interaction effect on mean compressive and shear forces. The average maximum values of compressive force did not exceed recommended load limits. However, the average maximum values of shear force exceeded recommended load limits repeatedly by more than 30%, which clearly indicates a health risk. The findings of this biomechanical approach were compared to an assessment with the Key Indicator Method for pushing and pulling, which is a conventional observational method for risk assessment. The comparison indicated that this conventional method might systematically underestimate the influence of some environmental factors in the forest and thus may also underestimate a potential health risk.

Keywords: biomechanics, compressive force, shear force, ergonomics, pulling, motor-manual timber harvesting

Introduction

Manual forestry work is a physically demanding job. Work-related musculoskeletal disorders (WMSD) and occupational accidents occur more frequently compared to other occupations (Federal Ministry of Food and Agriculture, 2017.) Back injuries or even herniated discs are the most commonly reported WMSD (Hoy et al., 2010). The health risk of manual forestry work is difficult to assess with conventional observation methods such as the Rapid Upper Limb Assessment (McAtamney & Corlett 1993) or the Ovako Working Posture Analysis System (Karhu et al., 1977). For these assessments, mainly the body posture and the load to be handled have to be analyzed (David, 2005). A general risk value is then determined to decide which, if any, measures need to be taken. While the Key Indicator Method, another conventional risk assessment method, additionally considers some environmental factors (Klussmann et al., 2010), these do not cover some of the specific conditions that are found in forestry work.

Environmental factors in the forest change dynamically even within a working day. They are much more complex and demanding than in the manufacturing industry, where conventional observation methods are widely applied. Some work operations, such as felling, may be sufficiently assessed using these methods, since the most influencing factors for an assessment of a potential health risk during lifting and holding tasks are the body posture and the load to be handled. Even though further analysis of hand-arm vibration may be required. The Key Indicator Method for pushing and pulling might be sufficient to analyze tasks related to motor-manual wood harvesting such as skidding since it considers some environmental factors in the assessment. However, the method is mainly focused on pushing and pulling of carriages or barrows and therefore not optimal for assessing skidding with the challenging environmental factors in the forest affecting this work activity.

There are very few studies that investigate physical workload during skidding. For example, Berendt et al. (2020) showed that metabolic strain is frequently high during this activity. Further investigations on whether this physical workload also causes back injuries or WMSD have, to the best of our knowledge, not yet been reported. Characteristic biomechanical parameters such as compressive force (CF) and shear force (SF) on the intervertebral discs can be used to analyze physical load on the back. These values, compared with recommended load limits, can provide an indication of health risk. Therefore, analysis of CF and SF may provide an indication of the causes of frequently occurring back injuries in manual forestry work.

The Key Indicator Method for pushing and pulling analyzes the environmental factors body posture, ground condition and soil slope. Berendt et al. (2020) identified an influence of soil slope on the metabolic strain during skidding. Laursen & Schibye (2002) could prove a correlation of CF and SF with ground condition in a study where containers were pulled on different ground surfaces. Both these studies indicate an influence of the task execution on the physical workload. Therefore the environmental factors to be investigated were derived as ground condition, soil slope and type of execution, which mainly changes the body posture during the task.

Based on the reasoning outlined above, a study was designed to investigate a potential risk for WMSD during skidding. The following research questions were derived:

1. Are biomechanical parameters suitable for identifying a potential health risk during skidding?
2. Which environmental variables contribute towards increased WMSD risk during skidding?

Methods

Motion capturing, force measures and biomechanical parameters analyze effects of environmental factors on physical workload for the activity of manually pulling a steel cable from a skidder winch over a distance of 20 meters in the forest. Based on literature, a biomechanical approach calculates CF and SF on the L5/S1 intervertebral disc using motion capture data from a full-body IMU-system and the pulling force from a DTS force sensor.

Biomechanical Approach

The calculation of the biomechanical parameters CF and SF for this field study is based on Jäger's theory (Jäger & Luttmann, 1992; Jäger et al., 2001). The average and maximum CF and SF on the L5/S1 intervertebral disc are calculated. This intervertebral disc is considered, because the highest load is assumed to impact there as others indicate in their studies (Glitsch et al., 2004; Bütting et al., 2017). Input factors are the body weight of the subjects, the tensile force to be applied, force direction, body posture and body acceleration. For this evaluation a MATLAB tool was developed. First, raw data are transferred and processed in the form of a frequency adjustment. This is necessary because the force sensor measures with a much higher frequency than the IMU-sensors. Furthermore, necessary intermediate calculations for e.g. acceleration forces, moments or the angle and position of the disc L5/S1 but also dynamic factors for the considered work action, such as cable angle, are performed before the CF and SF can be calculated.

Study design

This study was designed to investigate whether different environmental factors affect measurably physical work load during skidding as indicated by biomechanical parameters and whether the risk indicated by these parameters is comparable to that determined by a standard risk assessment method, specifically the Key Indicator Method for pulling and pushing. Three environmental factors represent the independent variables of this experiment and are summarized in Table 1. Figure 1 visualize the real conditions of the independent variables ground condition of this field experiment. The dependent variables were average compressive (CFmean) and shear forces (SFmean) on the L5/S1 disc. Each subject performed the work task eight times, i.e., in all combinations of the factor levels of the independent variables. The following hypotheses were formulated to analyze the influence of environmental factors on the physical workload of skidding:

- H01: Type of execution significantly affects the average CF and average SF on the L5/S1 disc.
- H02: Ground condition significantly affect the average CF and average SF on the L5/S1 disc.
- H03: Soil slope significantly affects the average CF and average SF on the L5/S1 disc.

The average maximum values of CF and SF are compared to recommended load limits to determine if a health risk can be identified (Gallagher & Marras, 2012; Jäger 2018). These findings are compared to risk assessment of the Key Indicator Method pushing and pulling.

Table 1: Independent variables and their factor levels for the conducted study

Independent variables	**Factor levels**
Type of execution	behind the back (A)
	over the shoulder (B)
Ground condition	without obstacles (C)
	with obstacles (D)
Soil slope	< 2% (1)
	> 4% (2)

Figure 1: Experimental conditions of the field study, left (without obstacles, < 2% soil slope), right (with obstacles < 2% soil slope)

Participants

The field study included 10 male professional foresters who were familiar with the work task. Exclusion criteria for participation in the study were having diagnosed back injuries. The mean age of participants was M=32.6 (SD=14.7). Their age ranged from 17 – 53 years.

Experimental setup

The study took place in the Arnsberg forest. Here, selected areas with different soil slope requirements offered a constant slope above 4% and a constant slope below 2%. For one of the lanes in each area, the ground was cleared as much as possible and on the other lanes the ground remained as it is. Each lane was measured to exactly 20 meters and marked with a start and finish line. The skidder was placed 1.5 meters in front of the start line to perform the respective measurements.

The measurement system consisted of a full body IMU-system with 14 myoMotion Reasearch Pro sensors and a DTS force sensor for data acquisition with MR3 myoResearch 3.14.76 software for control and synchronization. The skidder used was a Fendt Xylon 522 with a Pflanzelt fixed cable winche type 0308 and a PYTHON 6 R+F rope with 12 mm diameter.

Statistical Analysis

A MANOVA with repeated measures was calculated using SPSS version 28.0 software. Furthermore, descriptive statistics of maximum values for SF and CF were calculated and compared with recommended load limits from the literature. The results of the MANOVA were followed up with post-hoc ANOVA.

Results

The statistical assumptions for performing a MANOVA with repeated measures were tested and met (Field, 2013). Table 2 shows the results of the MANOVA. Statistically significant differences are shown in the combined dependent variables depending on type of execution, soil slope and the interaction of execution, ground conditions and soil slope. The univariate post-hoc analyses provide detailed information on the effects of the tested independent variables on the average SF and CF as Table 3 indicates. Post-hoc univariate ANOVA were conducted for every dependent variable. Results show statistically significant differences between the two factor levels of type of execution on CFmean and between the two factor levels of type of execution on SFmean. A statistically significant difference between the two factor levels of soil slope on CFmean was also indicated, but not on SFmean. Results yielded that there was a statistically significant difference between the combinations of type of execution, ground condition and soil slope on CFmean, as well as on SFmean on CFmean. Thus, the results demonstrated that there was sufficient evidence to accept the hypothesis H01 and H03. Hypothesis H02 had to be rejected.

Table 2: Results of multivariate tests of the conducted analysis

Variable	Wilks Lambda	F	Sig.	Partial Eta Squared
Type of execution	.174	18.989	<.001	.826
Ground condition	.834	.796	.484	.166
Soil slope	.375	6.669	.020	.625
Type of execution * Ground condition	.742	1.392	.303	.258
Type of execution * Soil slope	.750	1.334	.316	.250
Ground condition * Soil slope	.819	.886	.449	.181
Type of execution * Ground condition * Soil slope	.470	4.515	.049	.530

Table 3: Risk scores of the conducted study according to the Key Indicator Method pushing and pulling

Environmental factors	**Key indicator risk score**
Type of execution (A) * Ground condition (D) * Soil slope (1)	42.5
Type of execution (A) * Ground condition (C) * Soil slope (1)	47.5
Type of execution (B) * Ground condition (D) * Soil slope (1)	50
Type of execution (B) * Ground condition (C) * Soil slope (1)	55
Type of execution (A) * Ground condition (D) * Soil slope (2)	55
Type of execution (A) * Ground condition (C) * Soil slope (2)	60
Type of execution (B) * Ground condition (D) * Soil slope (2)	62.5
Type of execution (B) * Ground condition (C) * Soil slope (2)	67.5

The average maximum value of the CF is 2628.44 N, the age- and gender-specific recommended load limit according to Jäger is 3100 N for 50-year-old men (Jäger, 2018). The average maximum value of SF is 922.51 N, according to Gallagher exceeding 700 N, is considered a potential health risk for repetitive shear loading (Gallagher & Marras, 2012). The absolute maximum values are 4050.69 N for CF and 1311.80 N for SF.

The results of the assessment of the same activities using the Key Indicator Method are shown in Table 4. A daily work duration of 20 minutes was assumed for the evaluation. The evaluation of the type of execution is for A = 5 and for B = 8 points, ground condition factor level C = 3 points as well as D = 1 point. Soil slope is rated as 1 = 0 points and 2 = 5 points. All other factors were evaluated with 11 points in sum and kept constant. The risk intervals are subdivided from low (< 20 points) to slightly increased (20 - 50 points) and substantially increased (50 - 100 points) to high (> 100 points).

Table 4: Results of univariate tests of the conducted analysis

Variable	Measure	F	Sig.	Partial Eta Squared
Type of execution	CFmean	41.235	<.001	0.821
	SFmean	24.407	<.001	0.731
Ground condition	CFmean	1.791	0.214	0.166
	SFmean	0.906	0.366	0.091
Soil slope	CFmean	12.664	0.006	0.585
	SFmean	3.903	0.08	0.302
Type of execution * Ground condition	CFmean	0.99	0.346	0.099
	SFmean	3.098	0.112	0.256
Type of execution * Soil slope	CFmean	2.907	0.122	0.244
	SFmean	2.853	0.125	0.241
Ground condition * Soil slope	CFmean	0.528	0.486	0.055
	SFmean	1.936	0.198	0.177
Type of execution * Ground condition * Soil slope	CFmean	6.163	0.035	0.406
	SFmean	10.112	0.011	0.529

Discussion and Conclusions

This field study illustrates that environmental factors impact physical workload during skidding using the biomechanical parameters of CF and SF. A significant influence of the type of execution and soil slope was identified. On the other hand, no influence of the ground condition was found, which is in contrast to the findings of Laursen & Schibye (2002), who could prove a correlation with the ground condition in a study in which waste containers had to be pushed and pulled over different soil surfaces. The combination of type of execution, ground condition, and soil slope also showed a significant effect on mean CF and SF. Hypotheses H01 and H03 were therefore confirmed.

The univariate analysis of execution types reveals significant differences for both, the mean CF and the mean SF. Type of execution mainly affects the body posture, which is not specified in work instructions and is in part strongly dependent on individual behavior. Posture has a high significance in the ergonomic evaluation of work activities. The soil slope shows significant differences in the univariate tests only for the CF. The presence of a slope therefore affects the vertical forces more than the horizontal forces in the body; Berendt et al. (2020) also mention this. Combining type of execution, ground condition and soil slope shows significant differences for CF and SF. Argubi-Wollesen et al. (2017) concludes in a literature review investigating pushing and pulling activities, that with challenging environmental factors, physical workload increases as well. Assumingly, biomechanical parameters increase in the same way. Compared to the recommended load limits the average maximum SF values indicate a potential health risk from the actions of the field study conducted. Average maximum CF values do not exceed recommended load limits, although some individual values did.

The analysis with conventional observational methods also shows an immense influence of the body posture on physical load. However, difference in physical load estimated via the Key Indicator Method are predominantly based on differences in factor levels of soil slope. Thus, the Key Indicator Method suggests similar relationships to those found in the presented field study. That being said, the Key Indicator Method is not adequately adapted to the environmental factors in the forest. The selection of objects to pull or push is almost exclusively limited to barrows and carriages. Correspondingly, the evaluation of ground condition also focuses on objects with rolls and friction resistance. Overall, the evaluation of the Key Indicator Method shows that the work situation is assessed with an increased risk at most and is partially assessed with an acceptable risk. The analysis of the average maximum SF showed that recommended load limits are exceeded repetitively by more than 30%. Although an assessment using the Key Indicator Method gives a good indication, a potential health risks could be underestimated with this method. Thus, this study indicates that biomechanical parameters can be used to identify potential health risks in forestry work and to analyze them more accurately than with conventional observation methods. It also indicates that the Key Indicator Method might need to be adapted in order to account for more varied environmental conditions such as those found in forestry work.

Limitations occurring in this field study include the small sample size with 10 participants, resulting in reduced statistical power and less chances on finding existing correlations at a statistically significant level. The individual behavior of the subjects might also have had an influence on the measurement results. This is particularly evident in the analysis of the maximum values. The absolute maximum value of the CF is about 70% higher than the mean maximum value of the CF. With an increased number of participants, this difference might also reduce. Therefore, the mean maximum values had to be compared with recommended load limits. Finally, the significant 3-way interaction effect on CF and SF mean values indicate more complex effects that cannot be interpreted on the basis of this study and therefore need to be investigated in further research.

High physical workload, many occupational accidents and WMSD characterize manual forestry work. This paper presents a procedure for analyzing forest work using biomechanical parameters. The results indicate potential health risks in skidding, as the type of execution and soil slope were observed to have a significant influence on biomechanical parameters. The introduced applied biomechanical approach can identify these risks more accurately compared to traditional observational methods. These results contribute to a better identification of the physical workload in forestry and thus, in the long run, to the promotion of health at the workplace. In the future, further studies on different forest-specific conditions and with a larger number of participants should be carried out in order to gain further insights into health-related risks of forestry work.

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