Risks of Occupational Vibration Exposures

VIBRISKS

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Title: Effects of pior exposure to hand-transmitted vibration on vascular function

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Introduction

Workers who use hand-held vibratory tools may complain of vascular, neurological and musculoskeletal disorders of the upper extremities [12]. The principal vascular disorder associated with exposure to hand-transmitted vibration is vibration-induced white finger, a type of secondary Raynaud's phenomenon [4]. Vibration-induced white finger is a disorder characterised by complete episodic closure of digital blood vessels which results in attacks of well-demarcated finger blanching.

A medical interview is currently considered the best available method for diagnosing Raynaud’s phenomenon of either occupational or nonoccupational origin. The anamnestic diagnosis of vibration-induced white finger is based on a positive history of cold-induced episodes of finger whiteness occurring after the start of occupational exposure to hand-transmitted vibration, providing that primary Raynaud’s disease or other causes of secondary Raynaud’s phenomenon are excluded [17].

Cold provocation of the fingers and hands is a common testing procedure used in either clinical studies or epidemiological surveys to confirm objectively the existence of abnormal cold response in the digital vessels of vibration exposed workers affected with white fingers. The measurement of finger systolic blood pressure during cold provocation is considered an useful laboratory test for quantifying the degree of cold-induced digital vasospasm in vibration exposed workers [1, 3, 10, 16].

To assist in the implementation of uniform measuring methods and test conditions for the assessment of peripheral vascular function in vibration-exposed workers, the International Organisation for Standardisation (ISO) has recently approved the ISO Standard 14835-2 devoted to measurement and evaluation of finger systolic blood pressure during cold provocation [15]. The Standard specifies (i) the methods for measuring finger systolic blood pressures with local cold provocation, (ii) the procedures for conducting the measurements, and (iii) how to report the measurement results. The section of the Standard dedicated to measurement procedures includes items on subject preparation, with recommendations to subject to avoid strenuous physical exercise, smoking and caffeine for 3 h prior to examination; moreover, drinking of alcohol and intake of vasoactive medical drugs should be avoided during the twelve hours preceding the cold test. It is also recommended to avoid vibration exposure for at least 12 h prior to examination. According to the Standard, these restrictions should help to minimise possible adverse effects on the results of the cold test.

Researchers involved in epidemiological studies of vibration-exposed operators at workplace have often experienced that it may be hardly feasible to comply with the ISO recommendation about 12 h-avoidance of vibration exposure prior to conducting the cold test. Organisational aspects linked to work schedules or production cycles may impede to perform the cold test according to the time lag suggested by the ISO Standard.

The aim of this study was to investigate whether exposure to hand-transmitted vibration in controlled laboratory conditions can influence the cold response of digital vessels at various time-points after the application of a vibration stimulus. Moreover, since operating vibratory tools involves contact force exerted on tool handles, the effect of force with no vibration exposure on cold-induced digital vasoconstriction was also investigated.

Subjects and Methods

SUBJECTS

Ten healthy male volunteers, 8 Caucasian, 1 Asian and 1 African, gave written informed consent to participate in the investigation. All subjects were students or office workers with no history of regular use of hand-held vibrating tools in occupational or leisure activities. Seven subjects were non-smokers. None reported cardiovascular or neurological disorders, connective tissue diseases, injuries to the upper extremities, a history of cold hands or were on medication. The mean age of the subjects was 28.1 (SD 4.7; range 24 - 41) years, their mean stature was 180 (SD 5.8; range 168 - 187) cm and their mean weight was 78.8 (SD 9.2; range 65 - 97) kg.

COLD TEST

The cold test consisted of strain-gauge plethysmographic measurement of finger systolic blood pressure (FSBP) during local cooling according to the technique recommended by the International Standard ISO 14835-2 [15].

FSBP was measured in the thumb and index fingers of both hands. Latex pressure cuffs for water circulation were placed around the intermediate phalanx of the index fingers. Plastic pressure cuffs for air inflation (9.5 x 2.5 cm) were fixed around the proximal phalanx of each thumb and secured with a Velcro strip. Mercury-in-silastic strain gauges were placed around the distal phalanx at the base of the nails.

The two water cuffs, two air cuffs and four strain gauges were connected to a multi-channel plethysmograph (HV*Lab*, ISVR, University of Southampton).

The FSBP was measured at 30°C and 10°C with a cuff occlusion pressure of 250 mmHg and an occlusion duration of 5 minutes. Increases in finger volumes were detected by means of strain gauges according to the criteria given by by Greenfield et al [11].

The results of the cold test was expressed as the change of systolic blood pressure in the right and left index fingers (test fingers) at 10°C ($FSBP_{t,10°}$) as a percentage of the pressure at 30°C ($FSBP_{t,30°}$), corrected for the change of pressure in the right and left thumb fingers (reference fingers) during the examination ($FSBP_{ref,30°}$ - $FSBP_{ref,10°}$):

$$FSBP\%_{10°} = (FSBP_{t,10°} \times 100)/[FSBP_{t,30°} - (FSBP_{ref,30°} - FSBP_{ref,10°})] \qquad (\%)$$

The absolute change of FBSP in the test finger during cooling from 30° to 10°C, corrected for the change of pressure in the reference finger during the examination, was also estimated:

$$R\text{-}FSBP_{10°} = (FSBP_{t,30°} - FSBP_{t,10°}) - (FSBP_{ref,30°} - FSBP_{ref,10°}) \qquad (mmHg)$$

Brachial systolic and diastolic blood pressures were measured in the upper right arm by an ausculatatory technique.

Room temperatures were measured using a thermocouple located adjacent to the subjects' heads.

EXPERIMENTAL PROCEDURE

The experiment was performed in a laboratory room with a mean (SD) temperature of 26.0 (SD 0.5)°C. Recommendations to the subjects about smoking, drinking of alcohol, and caffeine consumption prior to examination were according to the ISO Standard 14835-2 [15].

Each of the 10 subjects attended the laboratory on 2 occasions. In each session, they experienced 9 successive experimental periods of varying durations (Table 1).

Throughout each session, subjects lay supine with their hands resting on platforms alongside their body at the level of the heart. After a period of acclimatisation of about 30 minutes during which the experimental set-up was arranged and the subject's fingers were instrumented, finger systolic blood pressure was measured at 30°C and 10°C (period A). A resting period of 10 minutes followed (period B). The right hand was then moved by the experimenter so the centre of the palm was positioned on a cylindrical wooden platform with a domed end (diameter 50 mm). During period C the subjects were asked to apply a downward force of 5 N with their palm on the platform that was mounted on an electrodynamic vibrator (VP4, Derritron). The signal from a force cell (Tedea Huntleigh) mounted between the platform and the vibrator was used to provide visual feedback on a meter for the control of downward force. All the fingers of the right hand were suspended in air (Figure 1). The left hand remained supported at heart height to the left of the body.

During period D, sinusoidal vertical vibration was presented for 60 minutes, followed by a 10-minute period with force without vibration during period E. The right hand was then moved by the experimenter, so that it was again supported on a platform at heart height alongside the subject for period F. FSBP was measured at 30°C and 10°C during period G. After a resting period of 20 minutes (period H), FSBP measurements at 30°C and 10°C were taken again (period I).

The vibration during period D had an acceleration magnitude of 64 ms^{-2} r.m.s. unweighted (8.0 ms^{-2} r.m.s. weighted) at 125 Hz. There was, additionally, a condition with force (5 N) but no vibration giving a total of two experimental conditions (Table 1).

For the 60-minute duration of vibration exposure, the 8-hour energy-equivalent frequency-weighted acceleration magnitude [$A(8)$] was 2.8 ms^{-2} r.m.s. in condition 2 according to International Standard ISO 5349-1 [14].

Brachial blood pressures were measured at the beginning and at the end of each experimental session. Room temperature was measured at 1-minute intervals.

Each of the ten subjects experienced both experimental conditions on separate days. Across the subject group, the two experimental conditions were presented in a balanced order. The experimental sessions lasted approximately 190 minutes. All sessions were completed within a three-week period.

The study was approved by the Human Experimental Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton (UK).

STATISTICAL METHODS

Data analysis was performed using the software package Stata (version 8.2 SE). The data were summarised with the mean as a measure of central tendency and the standard deviation (SD) or the range as measures of dispersion.

The difference between paired means was tested by the Student's *t* test.

An autoregressive model for repeated measures data set was used to test the hypothesis of no difference in the vascular responses in different exposure conditions over time, according to the following model form:

$$Y_{it} = \beta_0 + \beta_1(\text{time}) + \beta_2(\text{condition}) + \beta_3 Y_{it-1} + \varepsilon_{it}$$

where Y_{it} are FSBP measures for subject i at time t, β_0 is the intercept, β_1 is the regression coefficient for time, β_2 is the regression coefficient for condition, Y_{it-1} is the FSBP measure for subject i at time t – 1, β_3 is the autoregression coefficient, and ε_{it} is the 'error' for subject i at time t.

The assumption underlying the autoregressive model (also called transitional model) is that the value of an outcome variable at each time-point is primarily influenced by the value of this variable one measurement earlier [19].

The autoregressive model was processed using the generalised estimating equations (GEE) approach to repeated measures in order to account for the within-subject correlation [7].

The power of this repeated measures study with a three-period two-exposure design was computed by means of the software nQuery Advisor, release 5.0 [9]. For power calculations, the necessary information (variance of means, standard deviation at each level, correlation between successive levels, and effect size) were obtained from our previous experimental study of the acute effects of vibration on digital circulatory function in healthy men [2]. Using a 5% significance level, a sample size of 10 subjects (as in this investigation) was associated with 90% power to detect a difference in the means of repeated measures of the outcome variable (FSBP).

Results

REPEATABILITY OF THE COLD TEST

To test for the repeatability of FSBP measurements during finger cooling, the cold test was performed in five healthy men for five consecutive days (Table 2). Repeated measures analysis of variance showed no significant difference in the values of either $FSBP_{30°}$ (mmHg) or $FSBP\%_{10°}$ (%) by time. The coefficient of variation averaged 6.9% for $FSBP_{30°}$ (range 2.8 – 10.0%) and 6.3% for $FSBP\%_{10°}$ (range 3.8 – 9.3%). On the basis of these results, the repeatability of FSBP measures was considered to be acceptable for the purpose of practical applications of the cold test.

FINGER SYSTOLIC BLOOD PRESSURE BEFORE EXPOSURE

The vascular measurements before exposure to either contact force alone or contact force and vibration (see Table 1) showed no significant changes in FSBP at 30°C in either the exposed or the unexposed fingers across the two experimental sessions (p=0.12 – 0.86). During pre-exposure, FSBP at 30°C averaged 107 (SD 12.6) mmHg in the 1st right finger, 100 (SD 12.1) mmHg in the 2nd right finger, 100 (SD 12.9) mmHg in the 1st left finger, and 98 (SD12.6) mmHg in the 2nd left finger.

In the pre-exposure period, analysis of repeated measures by the GEE method showed no significant relation between FSBP at 30°C and room temperature in any finger. There was no significant difference in the air temperature of the laboratory over exposure periods (p=0.76) and across the two experimental sessions (p=0.54).

Subjects' age was not correlated with the baseline measures of FSBP.

Brachial systolic and diastolic arterial pressures measured before exposure did not change significantly within subjects across the two sessions (range of values across subjects and sessions: 110/70 – 140/80 mmHg). On a group basis, the mean value of brachial systolic arterial pressure at the beginning of the experimental sessions (123 mmHg) was higher than that measured at the end of sessions (116 mmHg, $p<0.01$), while no difference was observed for brachial diastolic arterial pressure (78 vs 77 mmHg, $p=0.64$).

COLD TEST AFTER EXPOSURE TO CONTACT FORCE AND VIBRATION

Analysis of repeated measures of FSBP (mmHg) at 30° and 10°C by the GEE method with an autoregressive model, showed no significant main effect of both exposure condition and exposure period (Table 3), with the exception for $FSBP_{30°}$ in the 1st right finger (exposed hand) and the 2nd left finger (unexposed hand) which showed a higher systolic pressure after exposure to condition 2 (contact force + vibration) than after condition 1 (exposure to contact force alone). There was no significant interaction between exposure conditions and exposure periods ($p>0.10$).

No significant changes in the FSBP indices during local cooling ($FSBP\%_{10°}$ and R-$FSBP_{10°}$) were observed across exposure conditions and over exposure periods in either the 2nd right finger (exposed hand) or the 2nd left finger (unexposed hand), (Table 4).

As expected, the predictor variable $FSBP_{(t-1)}$ (i.e. the value of FSBP measured one time-point earlier) was significantly related to the outcome variable FSBP at time-point *t*, expressed either as absolute values (mmHg) or as absolute or percentage changes at 10°C compared to 30°C (Tables 3 and 4).

Similar findings were observed when the results of the cold provocation test after exposure to contact force alone (condition 1) and exposure to contact force and vibration (condition 2) were analysed separately. There were no significant changes in $FSBP_{30°}$ (mmHg), $FSBP_{10°}$ (mmHg), $FSBP\%_{10°}$ (%), and R-$FSBP_{10°}$ (mmHg) at 30 and 70 minutes after exposure to either condition 1 (Tables 5 and 6) or condition 2 (Table 7 and 8).

Discussion

This laboratory study was designed to investigate whether prior exposure to vibration on the day of a cold provocation test may affect the cold response of digital arteries. The vibration magnitude and duration used in this study gave rise to a daily vibration exposure, $A(8)$, of 2.8 ms^{-2} r.m.s., i.e. slightly greater than the daily action value (2.5 ms^{-2} r.m.s.) established by the European Directive on mechanical vibration [8].

To our knowledge, there is no previous study which investigated whether conditions of exposure to contact force and hand-transmitted vibration, as when operating vibratory tools, are likely to influence the results obtained from an objective diagnostic test that is used to detect peripheral vascular symptoms.

In this study, analysis of repeated measures of FSBP during local cooling showed no significant changes in the cold response of digital arteries over time in both the right and the left hand after 60-min exposure of the right hand to contact force (5 N) combined with 125-Hz vibration with an unweighted acceleration magnitude of 64 ms^{-2} r.m.s. Moreover, no significant difference in cold-induced vasoconstriction of the digital arteries was found between exposure to contact force alone and combined exposure to contact force and vibration.

These findings suggest that in healthy men recent exposure to contact force and hand-transmitted vibration does not seem to influence adversely the response of finger circulation to cold provocation. Further research is needed to investigate to what extent our experimental findings can be applied to vibration exposed workers affected with peripheral vascular symptoms.

In this investigation, the coefficient of variation for FSBP% during local cooling to 10°C averaged 6% in healthy subjects. This finding is consistent with the results of previous studies of the repeatability of FSBP measurements in which the coefficient of variation for repeated determinations of FSBP% at 6° or 10°C was found to average between 5 and 13% in either normal individuals or vibration exposed workers [6, 13, 18].

In our previous study of cold provocation testing in a sample of 455 control subjects and 874 vibration exposed workers, of whom 17% affected with white fingers, the sensitivity of FSBP measurement to detect abnormal cold response of digital arterial vessels was 87%, the specificity 94%, the positive predictive value 75%, and the negative predictive value 97% [5].

These results, as well as those from investigations on FSBP% repeatability, tend to confirm the findings of previous studies which suggest that the measurement of FSBP during local cooling is a valid laboratory method to detect abnormal cold response in the digital blood vessels of vibration exposed workers [1, 3, 10, 17, 18].

This experimental study of the influence of prior vibration exposure on cold test results in healthy men suggests that the measurement of FSBP during local cooling 30 to 70 minutes after vibration exposure is not associated with adverse effects on the cold response of digital arteries.

This finding is consistent with the suggestion included in the VIBRISKS protocol for epidemiological studies of hand-transmitted vibration (Work Package 1) that a time period of 2 hours between the last occupational exposure to tool vibration and the commencement of objective vascular testing is adequate to avoid acute circulatory effects caused by recent vibration exposure.

Our findings may be of practical help for investigators involved in clinical and epidemiological studies of vibration exposed workers.

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Table 1. Experimental design of the study: condition of exposures to contact force alone (newtons) and combination of contact force and vibration with a frequency of 125 Hz and an unweighted acceleration magnitude of 64 ms^{-2} r.m.s.

Exposure period	Time interval (min)	Condition 1		Condition 2	
		Force	Vibration	Force	Vibration
A†	0 – 30	0	0	0	0
B	30 – 40	0	0	0	0
C	40 – 50	5 N	0	5 N	0
D	50 – 110	5 N	0	5 N	125 Hz, 64 ms^{-2}
E	110 – 120	5 N	0	5 N	0
F	120 – 130	0	0	0	0
G†	130 – 150	0	0	0	0
H	150 – 170	0	0	0	0
I†	170 – 190	0	0	0	0

†Cold test with measurement of finger systolic blood pressure at 30° and 10°C

Table 2. Finger systolic blood pressure at 30°C ($FSBP_{30°}$ in mmHg) and at 10°C as a percentage of the pressure at 30°C ($FSBP\%_{10°}$) in five subjects tested for five consecutive days. Mean values, standard deviations (SD), and coefficients of variation (CV in %) are reported.

Subject	$FSBP_{30°}$ (mmHg)			$FSBP\%_{10°}$ (%)		
	Mean	SD	CV	Mean	SD	CV
1	86	8.3	9.7	99.7	4.5	4.5
2	104	5.8	5.6	91.4	6.6	7.2
3	113	11.3	10.0	98.2	9.1	9.3
4	117	7.6	6.5	87.3	5.7	6.5
5	111	3.1	2.8	98.4	3.7	3.8

Table 3. Regression coefficients and robust 95% confidence intervals (estimated by a generalised estimating equations analysis with an autoregressive model) between finger systolic blood pressure (FSBP in mmHg) at 30°C and 10°C in the reference and cooled fingers (outcome variable) and exposure condition [exposure of the right hand to contact force alone (5 N for 80 minutes) or combined exposure to contact force (5 N for 80 minutes) and 125-Hz vibration (unweighted acceleration magnitude of 64 ms^{-2} r.m.s. for 60 minutes)], exposure period, and the value of the outcome variable one measurement earlier ($FSBP_{(t-1)}$).

Independent variables	1st right finger (reference finger, exposed hand)		2nd right finger (cooled finger, exposed hand)		1st left finger (reference finger, unexposed hand)		2nd left finger (cooled finger, unexposed hand)	
	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)
Intercept	30.9 (-1.3 – 63.0)	28.2 (4.7 – 51.7)	42.0 (14.2 – 69.8)	26.7 (5.4 – 48.0)	25.3 (2.8 – 47.8)	29.4 (-14.7 – 73.7)	39.8 (27.3 – 52.3)	6.7 (-19.1 – 32.5)
Exposure period	2.5 (-3.9 – 9.0)	3.3 (-2.2 – 8.9)	6.7 (-0.2 – 13.6)	4.2 (-3.6 – 12.0)	0.5 (-4.2 – 5.2)	0.3 (-6.2 – 6.8)	2.7 (-4.1 – 9.4)	1.0 (-5.9 – 7.8)
Exposure condition	4.0 (1.0 – 6.9)	-0.6 (-3.1 – 1.9)	0.5 (-2.9 – 3.9)	0 (-5.4 – 5.4)	0.4 (-3.3 – 4.2)	-0.12 (-1.6 – 1.3)	4.8 (0.1 – 9.5)	3.1 (-0.9 – 7.1)
$FSBP_{(t-1)}$	0.7 (0.4 – 1.0)	0.7 (0.5 – 0.9)	0.6 (0.4 – 0.9)	0.7 (0.6 – 0.9)	0.8 (0.6 – 1.0)	0.7 (0.3 – 1.1)	0.6 (0.5 – 0.8)	0.9 (0.6 – 1.2)

Table 4. Regression coefficients and robust 95% confidence intervals (estimated by a generalised estimating equations analysis with an autoregressive model) between finger systolic blood pressure (FSBP) indices during cold test at 10°C (outcome variable) and exposure condition [exposure of the right hand to contact force alone (5 N for 80 minutes) or combined exposure to contact force (5 N for 80 minutes) and 125-Hz vibration (unweighted acceleration magnitude of 64 ms^{-2} r.m.s. for 60 minutes)], exposure period, and the value of the outcome variable one measurement earlier (FSBP index $_{(t-1)}$).

Independent variables	2nd right finger (exposed hand)		2nd left finger (unexposed hand)	
	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)
Intercept	43.3 (-2.7 – 89.4)	5.1 (-2.4 – 12.5)	32.7 (-9.7 – 75.1)	4.3 (-0.4 – 9.1)
Exposure period	- 2.5 (-10.8 – 5.9)	3.2 (-5.3 – 11.8)	0.4 (-3.6 – 4.3)	0.6 (-4.2 – 5.3)
Exposure condition	2.0 (-4.8 – 8.8)	- 2.3 (-9.1 – 4.5)	- 2.0 (-7.3 – 3.2)	2.6 (-3.9 – 9.1)
FSBP index $_{(t-1)}$	0.5 (0.1 – 0.9)	0.5 (0.1 – 1.0)	0.6 (0.2 – 1.1)	0.7 (0.2 – 1.1)

Table 5. Finger systolic blood pressures (FSBP, mmHg) at 30° and 10°C in 10 healthy men before and after exposure of the right hand to contact force (5 N). Data are given as means (SD) [range]. P-values for repeated measures of FSBP over exposure periods were estimated by a generalised estimating equations analysis with an autoregressive model.

Condition 1: Contact force (5 N)	1st right finger (reference finger, exposed hand)		2nd right finger (cooled finger, exposed hand)		1st left finger (reference finger, unexposed hand)		2nd left finger (cooled finger, unexposed hand)	
	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)
Period A (pre-exposure)	110 (13.7) [93 – 138]	108 (14.4) [89 – 127]	100 (15.9) [79 – 125]	99 (18.3) [77 – 120]	101 (13.6) [77 – 121]	106 (11.5) [84 – 119]	101 (13.6) [80 – 122]	95 (10.5) [83 – 117]
Period G (30 min after exposure)	112 (11.5) [94 – 133]	108 (11.9) [98 – 139]	104 (13.4) [85 – 128]	100 (19.8) [67 – 124]	105 (12.8) [86 – 126]	106 (10.9) [84 – 125]	104 (14.0) [85 – 123]	96 (13.6) [67 – 112]
Period I (70 min after exposure)	111 (14.7) [87 – 139]	112 (13.2) [89 – 135]	114 (13.6) [84 – 135]	103 (16.6) [73 – 116]	109 (13.7) [83 – 131]	110 (13.8) [80 – 131]	108 (13.3) [83 – 131]	95 (15.0) [75 – 117]
P-value	0.53	0.41	0.12	0.72	0.96	0.25	0.78	0.63

Table 6. Finger systolic blood pressure indices during cold test at 10°C in 10 healthy men before and after exposure of the right hand to contact force (5 N). Data are given as means (SD) [range]. P-values for repeated measures of FSBP over exposure periods were estimated by a generalised estimating equations analysis with an autoregressive model.

Condition 1: Contact force (5 N)	2^{nd} right finger (exposed hand)		2^{nd} left finger (unexposed hand)	
	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)
Period A (pre-exposure)	100.4 (9.4) [82.3 – 118.2]	0 (8.4) [-12 – 18]	89.7 (10.5) [74.6 – 105.3]	11.5 (11.8) [-5 – 29]
Period G (30 min after exposure)	99.4 (16.1) [74.4 – 130.5]	0.7 (15.6) [-29 – 23]	92.4 (13.2) [66.3 – 111.6]	8.5 (13.7) [-10 – 34]
Period I (70 min after exposure)	88.8 (10.4) [67.0 – 102.7]	13.0 (11.9) [-3 – 36]	87.8 (12.1) [67.6 – 103.6]	13.8 (13.4) [-3 – 36]
P-value	0.20	0.14	0.24	0.14

Table 7. Finger systolic blood pressures (FSBP, mmHg) at 30° and 10°C in 10 healthy men before and after combined exposure of the right hand to both contact force (5 N for 80 minutes) and 125-Hz vibration (unweighted acceleration magnitude of 64 ms^{-2} r.m.s. for 60 minutes). Data are given as means (SD) [range]. P-values for repeated measures of FSBP over exposure periods were estimated by a generalised estimating equations analysis with an autoregressive model.

Condition 2: Contact force (5 N) & Vibration (125 Hz, 64 ms^{-2} r.m.s.)	1st right finger (reference finger, exposed hand)		2nd right finger (cooled finger, exposed hand)		1st left finger (reference finger, unexposed hand)		2nd left finger (cooled finger, unexposed hand)	
	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)	$FSBP_{30°}$ (mmHg)	$FSBP_{10°}$ (mmHg)
Period A (pre-exposure)	104 (11.9) [86 – 122]	111 (12.9) [95 – 127]	99 (8.2) [87 – 117]	97 (14.2) [68 – 116]	99 (13.4) [71 – 120]	105 (13.5) [86 – 125]	95 (12.0) [75 – 117]	91 (13.1) [72 – 113]
Period G (30 min after exposure)	107 (14.6) [87 – 128]	110 (11.8) [90 – 128]	105 (10.1) [90 – 119]	97 (16.0) [61 – 118]	104 (10.4) [81 – 119]	110 (10.9) [85 – 125]	104 (12.7) [86 – 129]	93 (17.9) [73 – 131]
Period I (70 min after exposure)	116 (10.0) [98 – 126]	113 (12.5) [97 – 130]	115 (10.3) [93 – 128]	103 (12.8) [75 – 115]	109 (15.4) [74 – 123]	109 (10.9) [89 – 127]	113 (11.9) [93 – 131]	98 (18.3) [79 – 140]
P-value	0.12	0.37	0.13	0.25	0.86	0.25	0.48	0.30

Table 8. Finger systolic blood pressure indices during cold test at 10°C in 10 healthy men before and after combined exposure of the right hand to both contact force (5 N for 80 minutes) and 125-Hz vibration (unweighted acceleration magnitude of 64 ms^{-2} r.m.s. for 60 minutes). Data are given as means (SD) [range]. P-values for repeated measures of FSBP over exposure periods were estimated by a generalised estimating equations analysis with an autoregressive model.

Condition 2: Contact force (5 N) & Vibration (125 Hz, 64 ms^{-2} r.m.s.)	2nd right finger (exposed hand)		2nd left finger (unexposed hand)	
	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)	$FSBP\%_{10°}$ (%)	$R\text{-}FSBP_{10°}$ (mmHg)
Period A (pre-exposure)	91.7 (8.1) [73.9 – 99.0]	8.5 (7.5) [1 – 24]	90.6 (11.2) [79.0 – 108.9]	10.0 (12.0) [-8 – 28]
Period G (30 min after exposure)	89.3 (13.0) [58.1 – 104.0]	11.7 (13.9) [-4 – 44]	84.3 (6.9) [72.3 – 91.7]	16.8 (6.8) [9 – 29]
Period I (70 min after exposure)	93.2 (11.1) [75.4 – 117.4]	8.0 (12.1) [-17 – 28]	87.4 (14.7) [61.2 – 105.3]	15.1 (19.1) [-6 – 50]
P-value	0.32	0.32	0.12	0.30

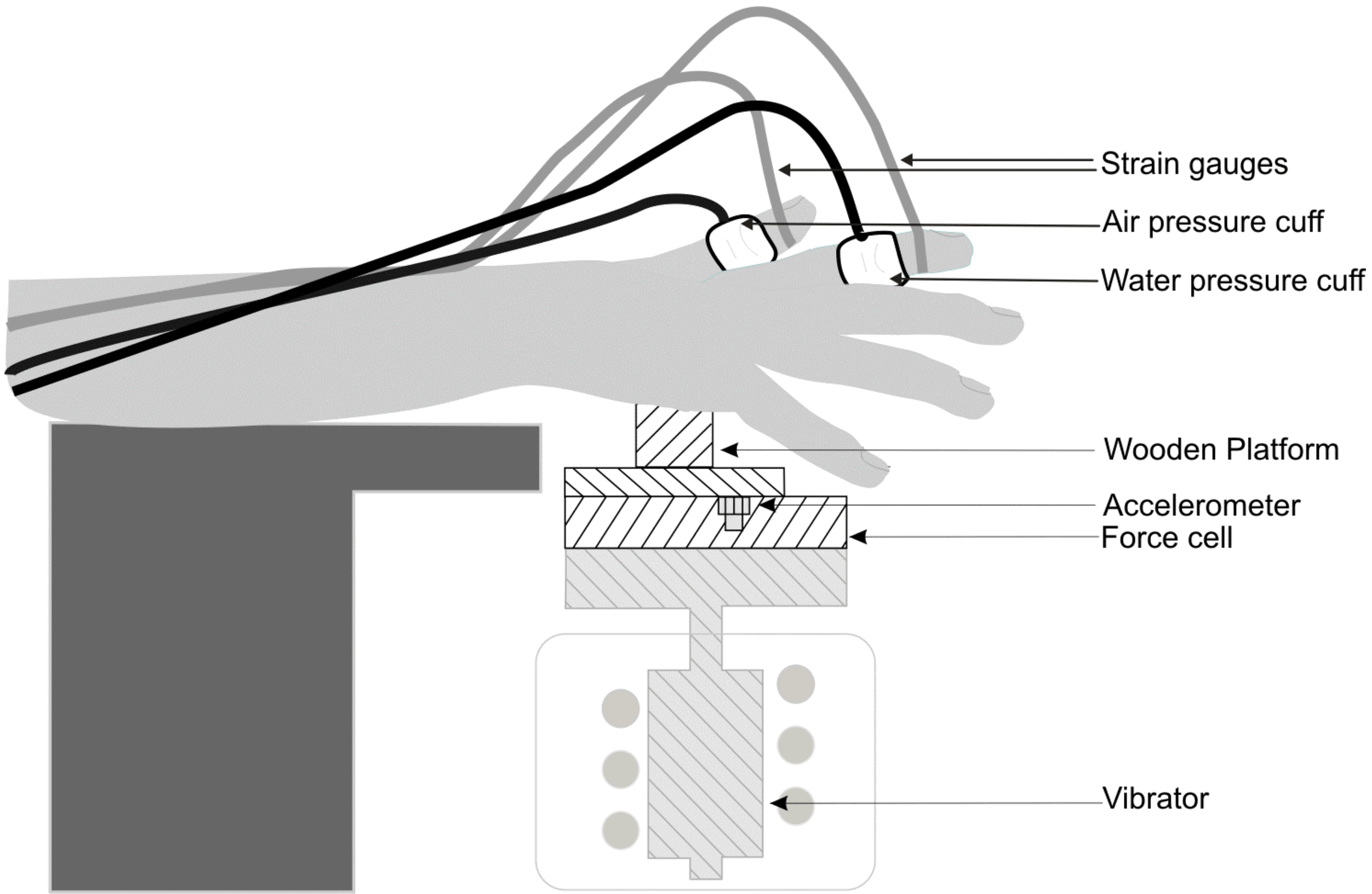

Figure 1. Experimental set-up for generating and measuring the vibration, controlling the contact force at the palm, and detecting finger blood flow signals.