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A Portable Heat-Exchange-Based System for Assessing Digital Vascular Response to Cold

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Abstract

Background: *Digital vascular assessment is relevant in occupational medicine, but current measurement methods may be complex and poorly portable.* **Objective:** *To validate a portable heat-exchange-based system for assessing cold-induced digital vascular response, using strain-gauge plethysmography as the reference method.* **Methods:** *Twenty healthy volunteers, 10 males and 10 females, underwent five subsequent sessions. Finger blood flow (FBF) was assessed by strain-gauge plethysmography, while simultaneously, fingertip thermal power (TP) was recorded with a portable thermoflowmeter. FBF was measured at baseline, while both FBF and TP were measured during application of 1-N contact force alone and during 1-N force combined with local cooling at 10 °C. The relationship between TP and FBF, after adjustment for covariates (age, sex, body mass index (BMI), and room temperature), was evaluated in the cooled condition using a linear mixed model including fixed and random effects.* **Results:** *Local cooling induced a significant vascular response, with FBF decreasing from 1.23 to 0.98 ml/100 ml/s ($p<0.0001$). In the cooled-condition model, TP was significantly associated with FBF, with each 1 ml/100ml/s increase in FBF corresponding to a 39.6 mW increase in TP ($p<0.0001$). Under cooling, TP showed lower within-subject variability than FBF (wsCV ≈0.19 vs ≈0.64). BMI was positively associated with TP (4.40 mW per kg/m^2, $p=0.007$), whereas age and sex were not significant predictors.* **Conclusions:** *These findings support the interpretation of TP as a perfusion-related thermal descriptor with potential applicability in occupational health surveillance. Further validation in subjects with digital vascular disorders is needed.*

1. Introduction

Exposure to hand-transmitted vibration represents a significant occupational hazard for the development of digital vascular disorders, such as vibration-induced white finger (VWF), which represents a secondary form of Raynaud's phenomenon [1]. Evidence of this phenomenon appeared as early as the 1900s, when Loriga (1911) and then Hamilton (1918) observed cases of digital pallor among workers exposed to pneumatic hammers, highlighting the role of mechanical and thermal

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stimuli in the genesis of vascular disorders [2]. In the following decades, several epidemiological and experimental studies demonstrated a strong association between exposure to hand-transmitted vibration and cold exposure and digital vasospasm [3]. VWF has a multifactorial pathogenesis, characterized by recurrent episodes of digital pallor, pain, and tingling, typically triggered by cold exposure. These manifestations result from vascular injury caused by repeated hand-transmitted mechanical stress, and are with increased autonomic nervous system activity and dysregulated vascular tone [1, 3-5]. Cold exposure acts as a powerful vasoconstrictor, which reduces blood flow and precipitates ischemic episodes [4, 6]. In occupational medicine, objective assessment of digital vascular function (e.g., measurement of finger systolic blood pressure with cold challenge by plethysmography, or digital thermal monitoring) is crucial as a complementary assessment in the early diagnosis of vibration-induced vascular disorders and to identify countermeasures. Although several validated instrumental techniques are available [7], many are difficult to use in routine practice. Strain-gauge plethysmography (SGP) is a well-established non-invasive method for measuring finger systolic blood pressure during cold provocation in vibration-exposed workers [8, 9] and for monitoring changes in finger blood flow induced by vibration and/or cold in experimental settings [10, 11]. Nevertheless, the use of SGP in clinical practice is limited by practical constraints, including the need for tightly controlled environmental conditions, technical complexity, long test duration, and limited portability. As a result, its application is mostly confined to specialized settings.

In this context, developing a new tool for occupational physicians to use during workplace health surveillance could be of great interest.

The present study aimed to provide a preliminary validation of a portable device that measures heat exchange between the fingertip and a cold surface to assess the digital vascular response to cold. The physiological rationale for this approach is based on the role of blood perfusion in heat transport from the core of the body to peripheral tissues. When a fingertip is placed in contact with a colder surface, the measured heat exchange depends not only on the imposed temperature gradient and the thermal properties of the skin-surface interface, but also on the amount of heat delivered to the fingertip by local circulation. Experimental evidence indicates that digital blood flow influences the skin cooling response during contact with cold surfaces, with different thermal responses observed under arterial occlusion and vasodilated conditions [12]. Therefore, thermal power measured by a thermoflowmeter is considered a potentially perfusion-related thermal descriptor and an indirect measure of digital blood flow.

2. Materials and Methods

2.1. Study Population

The study was conducted on a sample of 20 healthy volunteers (10 males and 10 females), aged 18 to 46 years, recruited among university students and hospital staff. Inclusion criteria required the absence of known cardiovascular or metabolic diseases. Individuals who were current or former smokers were excluded due to the well-established effects of smoking on peripheral vascular function. All participants provided written informed consent before inclusion in the study. The experimental procedures were conducted in accordance with the Declaration of Helsinki and approved by the ethical committee of Politecnico di Milano (auth. 41/2025).

2.2. Measurement Systems

Two measurement systems were used to assess digital vascular function: a strain-gauge plethysmograph (HVLab) for measuring finger blood flow (FBF), and a thermal power (TP) measurement system (thermoflowmeter, hereafter referred to as TFM) designed to quantify heat exchange between the fingertip and a temperature-controlled surface. The study aimed to investigate the relationship between TP and FBF under controlled experimental conditions and to assess the feasibility of using thermal measurements as an indirect indicator of peripheral perfusion.

2.2.1 Strain-Gauge Plethysmography (HVLab)

FBF was assessed by venous occlusion strain-gauge plethysmography, a reference method for the

quantitative evaluation of peripheral circulation. An indium-in-silicone strain-gauge was placed circumferentially around the distal phalanx of the right index finger, while a pneumatic cuff positioned at the base of the finger was inflated to approximately 60 mmHg to occlude venous outflow while maintaining arterial inflow. Under these conditions, arterial inflow produces a progressive increase in finger volume, which is detected as a change in the strain-gauge's electrical resistance. FBF was estimated from the initial linear slope of the volume increase following cuff inflation, according to the venous occlusion principle described by Greenfield et al. [13]. Blood flow values are expressed as ml/100 ml/s.

2.2.2 Thermal Power Measurement System (TFM)

Digital perfusion was also evaluated using a system that measured TP exchange between the fingertip and a temperature-controlled surface. The sensing unit consists of a thermally conductive metal plate whose temperature is actively regulated by a thermoelectric module controlled via a proportional-integral feedback loop based on resistance temperature detectors. When the fingertip is placed in contact with the surface, heat is transferred from the tissue to the plate by conduction. The system measures the rate of heat transfer exchanged between the finger and the cooled interface, which is influenced by local blood perfusion [12]. A load cell integrated beneath the contact surface continuously measures the force applied by the fingertip. Monitoring contact force is essential because it affects thermal contact resistance and the effective contact area, making it a major source of variability independent of physiological changes [14]. The system continuously records TP (mW) and applied force (N) during the measurement period, allowing the assessment of both transient and steady-state thermal responses.

2.3 Experimental Protocol

All measurements were performed in a temperature-controlled laboratory environment. Upon arrival, participants underwent a 15-minute acclimatization period in a seated position. Anthropometric parameters (height and weight), brachial blood pressure, and baseline finger skin temperature (FST) were recorded before the experimental session. Brachial systolic and diastolic blood pressures were measured in the left upper arm using an auscultatory technique. FST was measured using K-type thermocouple at the beginning of the test: participants pinched one end of the thermocouple between their thumb and index finger. The room temperature (RT) was measured by the same thermocouple, which was placed on the table where the tests were performed. Participants were seated comfortably with their right hand positioned at heart level. FBF and TP measurements were performed on the right index finger. The positioning of the finger on the TFM surface for the acquisition of force and thermal signals, together with the plethysmographic setup, is shown in Figure 1 (left panel).

Each participant underwent a standardized experimental protocol consisting of three consecutive phases, performed within a single session and repeated on five separate days:

1. Baseline: No external force or thermal stimulus was applied. FBF was measured using strain-gauge plethysmography only.
2. Force (1-N): participants were asked to apply a target force of approximately 1-N on the thermoflowmeter surface at room temperature. During this phase, FBF and TP were recorded simultaneously.
3. Force + cold (1-N, 10 ˚C): participants were asked to apply a target force of approximately 1-N while the finger was in contact with the temperature-controlled surface set at 10 ˚C. Both systems recorded data simultaneously.

Each phase lasted 100 seconds. During each phase, FBF was measured by repeated venous occlusion cycles (10 measurements over 100 seconds), each including cuff inflation to 60 mmHg followed by recording of the fingertip volume increase. At the same time, the TFM continuously recorded TP (mW) and the applied force (N) throughout the entire phase. A schematic representation of the experimental protocol is provided in Figure 1 (right panel).

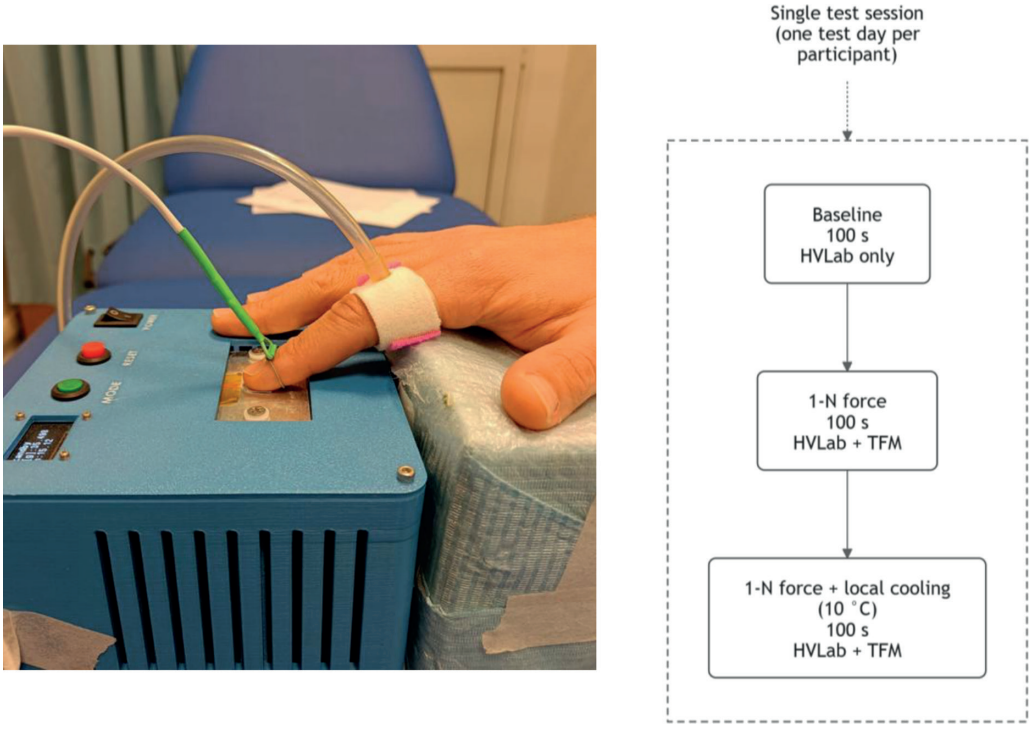

Figure 1. Left panel: positioning of the participant's right index finger on the TFM surface for simultaneous acquisition of contact force and TP; FBF was measured simultaneously using the strain-gauge plethysmograph (HVLab), with the strain-gauge positioned around the right index finger. Right panel: schematic representation of the experimental protocol during a single test session, consisting of three consecutive phases: baseline (HVLab only), application of a 1-N contact force (HVLab + TFM), and combined 1-N force with local cooling at 10 °C (HVLab + TFM). Each phase lasted 100 seconds.

2.4 Statistical Analysis

Statistical analyses were performed using the Stata software (version 19 SE; StataCorp, College Station, TX, USA). Continuous variables were summarized as means, standard deviations (SD), or 95% confidence intervals (95% CI). For FBF, the value used for each participant, session, and experimental condition was the mean of the 10 consecutive plethysmographic measurements acquired during each 100-second phase. For TP, the mean value was calculated from all samples recorded during the same period. Between-group comparisons (males *vs* females) for baseline characteristics were made using an unpaired Student's *t*-test. Within-subject comparisons between experimental conditions were assessed using a paired Student's *t*-test. A p-value <0.05 (two-sided) was set as the limit of statistical significance. The variability and repeatability of repeated measurements over the five consecutive experimental days were evaluated by calculating the repeatability coefficient (RC) and the within-subject coefficient of variation (wsCV), according to the Bland and Altman approach [15]. The relationship between TP and selected covariates, including age, sex, body mass index (BMI), RT, and FBF, was investigated using linear mixed-effects regression models with robust standard errors (rSE) to account for repeated measurements within subjects. The models included a random-intercept term at the subject level and a random slope on FBF. Model performance was assessed using R-squared values to estimate the proportion of variance explained by fixed and random effects.

3. Results

The individual characteristics of the study participants are reported in Table 1. Males and females were comparable in age and BMI, whereas males were significantly taller and heavier than females. Environmental and baseline physiological conditions were stable across the five experimental sessions. In the total sample, RT averaged 24.5°C (95% CI: 24.3-24.8). Similarly, baseline FST averaged 31.0°C (95% CI: 30.3-31.8), with limited variability (wsCV ≈0.097) and no significant sex-related differences (p=0.334).

FBF measurements under the different experimental conditions are summarized in Table 2. No significant differences were observed between baseline and the 1-N force condition in the total sample (mean 1.22 vs 1.23 ml/100 ml/s; p=0.90) or when stratified by sex (males: p=0.22; females: p=0.38). Within-subject variability was similar across experimental conditions. In the total sample, wsCV values were 0.59, 0.61, and 0.64 for baseline, 1-N force, and 1-N force plus cold conditions, respectively, with comparable repeatability coefficients. Exposure to local cooling was associated with a reduction in FBF. In the total sample, FBF decreased from 1.23 ml/100 ml/s (95% CI: 1.05-1.40) during the 1-N force condition to 0.98 ml/100 ml/s (95% CI: 0.83-1.13) during the combined force and cold condition (p<0.0001). FBF reduction was observed in both males and females.

TP results are presented in Table 3. In the total sample, TP increased markedly from 64.8 mW (95% CI: 54.0-75.6) under the 1-N force condition to 243.0 mW (95% CI: 230.6-255.4) during combined force and cold exposure (p<0.0001). TP increase was consistent across sexes and was associated with a reduction in within-subject variability under cold conditions (wsCV ≈0.19 vs ≈0.58 in the force-only condition), indicating improved repeatability when a thermal stimulus was applied.

The crude relationship between TP and FBF is illustrated in Figure 2. Linear regression analysis showed that TP increased with FBF according to the following fitted model: TP = 201.3 + 42.1(FBF). The association was statistically significant ($\chi^2(df\ 1) = 28.5$, $p < 0.0001$) and explained a substantial proportion of the variance ($R^2 = 0.56$), indicating a moderate-to-strong relationship between the two variables. The multivariable relationships of TP with individual, physiological, and environmental factors, investigated using linear mixed-effects models, are shown in Table 4. In the full model, FBF remained a significant predictor of TP (39.6 mW per 1 ml/100 ml/s increase in FBF, rSE = 7.52, $p < 0.0001$). Sex was not significantly associated with TP ($p = 0.84$). In sex-stratified analyses, FBF was significantly associated with TP in both males and females, although with different estimated regression coefficients (36.6 mW per 1 ml/100 ml/s increase in FBF for males; 56.4 mW per 1 ml/100 ml/s increase in FBF for females; both $p < 0.0001$). Among the other covariates, BMI was positively associated with TP (4.40 mW per kg/m^2, $p = 0.007$), while RT showed a weaker positive effect (6.71 mW per °C, $p = 0.064$). Age was not significantly associated with TP. The full model explained a substantial proportion of the variance in TP ($R^2 = 0.68$), with contributions from the fixed effects ($R^2 \approx 0.51$), the random intercept (≈ 0.10), and the random slope (≈ 0.06).

Table 1. Characteristics of the study participants. Data are given as means (SD).

	Females (n=10)	Males (n=10)	Total sample (n=20)
Age (yr)	34.6 (7.6)	35.6 (6.2)	35.1 (6.8)
Height (cm)	164 (5.4)	180 (9.7)[b]	172 (11.1)
Weight (kg)	64.1 (12.5)	76.7 (12.1)[a]	70.4 (13.6)
BMI (kg/m^2)	23.9 (4.6)	23.7 (2.9)	23.8 (3.7)

Males vs females: [a]p=0.034; [b]p=0.0003.

Table 2. Finger blood flow (FBF, ml/100 ml/s) measured over five consecutive days under baseline conditions, during application of a 1-N contact force, and during 1-N force combined with local cooling (10°C) in healthy subjects. The repeatability coefficients (RC) and the within-subject coefficients of variation (wsCV) for FBF are reported.

	FBF (ml/100 ml/s)		
Subjects	**Mean (95% CI)**	**RC (95% CI)**	**wsCV (95% CI)**
Males (n=10, obs=50)			
Baseline	1.13 (0.88-1.37)	2.10 (1.72-2.69)	0.67 (0.55-0.86)
1-N force	1.26 (1.02-1.50)	2.40 (1.97-3.08)	0.69 (0.50-0.88)
1-N force+cold 10°C	1.09 (0.87-1.32)[a]	2.15 (1.77-2.75)	0.71 (0.50-0.93)
Females (n=10, obs=50)			
Baseline	1.31 (1.04-1.59)	1.87 (1.54-2.40)	0.52 (0.42-0.66)
1-N force	1.20 (0.93-1.46)	1.65 (1.35-2.11)	0.50 (0.27-0.72)
1-N force+cold 10°C	0.88 (0.67-1.08)[b]	1.24 (1.01-1.58)	0.51 (0.27-0.75)
Total sample (n=20, obs=100)			
Baseline	1.22 (1.04-1.40)	1.99 (1.72-2.36)	0.59 (0.51-0.70)
1-N force	1.23 (1.05-1.41)	2.06 (1.79-2.44)	0.61 (0.45-0.76)
1-N force+cold 10°C	0.98 (0.83-1.14)[b]	1.75 (1.52-2.08)	0.64 (0.47-0.82)

95% CI: 95% confidence intervals.
Paired t-test (1-N force vs 1-N force+cold 10°C): [a]p=0.017; [b]p<0.0001.

Table 3. Thermal power (TP in mW) measured over five consecutive days in healthy males (n=10, obs=48) and females (n=10, obs=50) during exposure of the right index fingertip to 1-N push force alone or combined with local cooling to 10°C. The repeatability coefficients (RC) and the within-subject coefficients of variation (wsCV) for TP are reported.

	TP (mW)		
Subjects	**Mean (95% CI)**	**RC (95% CI)**	**wsCV (95% CI)**
Males (n=10, obs=48)			
1-N force	59.8 (42.8-76.8)	116.0 (93.2-153.3)	0.68 (0.28-1.08)
1-N force+cold 10°C	247.5 (229.6-265.5)[a]	142.0 (114.2-187.8)	0.20 (0.15-0.26)
Females (n=10, obs=50)			
1-N force	69.7 (55.7-83.6)	81.4 (66.2-105.7)	0.47 (0.27-0.67)
1-N force+cold 10°C	238.6 (220.9-256.3)[a]	119.0 (97.4-151.7)	0.18 (0.13-0.22)
Total sample (n=20, obs=98)			
1-N force	64.8 (54.0-75.6)	99.1 (84.9-119.1)	0.58 (0.37-0.78)
1-N force+cold 10°C	243.0 (230.6-255.4)[a]	130.0 (111.4-154.8)	0.19 (0.16-0.23)

95% CI: 95% confidence intervals.
Paired t-test (1-N force vs 1-N force+cold 10°C): [a]p<0.0001.

4. Discussion

The present study aimed to evaluate the feasibility and physiological relevance of a thermal power-based approach for assessing peripheral digital perfusion, using strain-gauge plethysmography as the reference method. The findings provide insight into both the robustness of the measurement protocol and the physiological interpretability of the thermal signal under controlled experimental conditions.

A preliminary aspect concerns the comparison between the baseline and the 1-N force condition. From a strictly physiological perspective, this comparison was not intended to reveal differences in vascular response, as no specific stimulus was

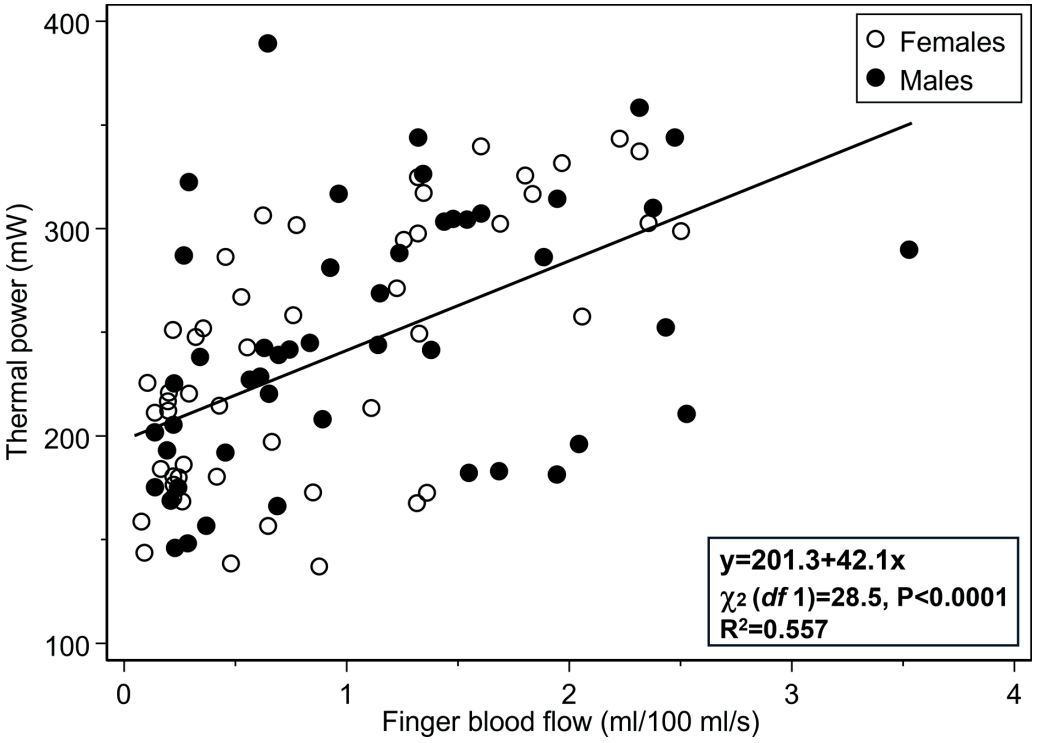

Figure 2. Association between thermal power (TP, mW) and finger blood flow (FBF, mL/100 mL/s) measured over five sessions in healthy males (n=10, observations=48) and females (n=10, observations=50) during exposure of the right index fingertip to a 1-N contact force combined with local cooling at 10 °C. The fitted line represents the crude regression of TP on FBF; the corresponding equation, test statistic, and R^2 are shown in the figure.

introduced. Rather, its primary purpose was methodological, namely, to validate the measurement protocol. Specifically, this test was designed to verify that the contact between the fingertip and the device surface, required for thermal measurements, did not interfere with the plethysmographic assessment of FBF, and that the selected force level was appropriate. The results support this assumption: FBF mean values were almost the same in the two conditions (1.22 vs 1.23 ml/100 ml/s in the total sample), with comparable within-subject variability (wsCV ≈ 0.59 vs 0.61). These findings indicate that a contact force of approximately 1-N does not produce measurable alterations in blood flow or in the strain-gauge signal under the adopted conditions. This is a desirable outcome, as moderate contact forces are required to ensure stable thermal contact while minimizing physiological perturbation. Therefore, the baseline *vs* 1-N comparison provided an internal validation of the experimental setup, suggesting that the measurement interface does not substantially bias measurements obtained under contact conditions.

In contrast, the combined exposure to a 1-N force and local cooling to 10°C produced a statistically significant reduction in FBF of about 20%. This effect was consistent across sexes and repeated sessions, indicating a robust vasoconstrictive response to cold exposure. These findings suggest that the cooling stimulus, even if limited to the fingertip, is sufficient to induce a measurable reduction in blood flow, indicating that digital circulation is highly sensitive to local temperature changes, despite its short duration. The magnitude and consistency of the observed effect support the adequacy of the experimental protocol for inducing physiologically meaningful changes in digital blood perfusion.

TFM measurements showed a marked, approximately fourfold, increase in TP under cooling

Table 4. Linear mixed-effects regression models of thermal power (TP in mW) on individual characteristics, room temperature (RT), and finger blood flow (FBF) in healthy males (n=10, obs=48) and females (n=10, obs=50) during exposure of the right index fingertip to 1-N push force and local cooling to 10°C. The model include a random-intercept term at the subject level and a random slope on FBF. Regression coefficients and robust standard errors (rSE) are adjusted for the effect of repeated measurements over time. The R-squared (R^2) measures for the models fit show the proportions of the total outcome (TP) variance attributed to fixed and random effects in the total sample and by sex.

	Males (n=10, obs=48)	**Females (n=10, obs=50)**	**Total sample (n=20, obs=98)**
Factors	**Coefficients (rSE)**	**Coefficients (rSE)**	**Coefficients (rSE)**
Age (yr)	3.47 (1.99)	1.17 (0.98)	1.29 (1.08)
Gender (M vs F)	-	-	-2.44 (12.28)
BMI (kg/m^2)	8.57 (2.05)[d]	2.39 (1.01)[a]	4.40 (1.64)[b]
RT (°C)	15.3 (5.59)[c]	3.08 (3.59)	6.71 (3.62)
FBF (ml/100ml/s)	36.6 (10.5)[d]	56.4 (9.23)[d]	39.6 (7.52)[d]
Constant	180.1 (19.6)	153.4 (10.6)	175.9 (11.6)
R^2 measures			
fixed slopes	0.48	0.67	0.51
random intercept	0.13	0.01	0.10
random slope	0.10	0.09	0.06
whole model	0.71	0.77	0.68
residuals	0.29	0.23	0.32

[a] p=0.018; [b] p=0.007; [c] p=0.006; [d] p<0.0001.

conditions. This finding is expected based on the physics of heat transfer, as thermal power is directly driven by the temperature gradient between the tissue and the contact surface. Lower interface temperatures increase the gradient and, therefore, the conductive heat flux required to maintain thermal equilibrium. This is consistent with the theoretical framework of the measurement system, in which heat flux depends on both boundary temperature and the overall skin-contact thermal resistance. In addition to increasing signal magnitude, cooling substantially improved measurement repeatability. The wsCV for TP decreased from approximately 0.58 in the non-cooled condition to about 0.19 under cooling, indicating a marked reduction in variability. This improvement can be attributed to the active control of interface temperature, which stabilizes one of the main sources of experimental uncertainty. Moreover, the higher absolute TP values under cooling likely contribute to an improved signal-to-noise ratio. This is consistent with the system's design, which is specifically intended to operate under a controlled cooling regime. Moreover, the wsCV observed for TP in cooled conditions (≈0.19) was lower than that of FBF (≈0.64), suggesting that the thermal measurement may offer better repeatability under controlled boundary conditions.

In the cooled condition, univariate regression analysis showed a positive and statistically significant association between TP and FBF. The fitted model explained a substantial proportion of the variability in TP ($R^2 \approx 0.56$) and confirmed that higher FBF was associated with greater heat transfer during local cooling. When extending the analysis to multivariable linear mixed models with fixed and random effects, the association between TP and FBF remained significant in both the entire sample and after stratification by sex. Nevertheless, in the sex-stratified analysis, the association between TP and FBF was stronger in females than in males. A plausible explanation is that sex-related differences in fingertip skin structure influence heat transfer between the finger and the cooled surface. Previous studies have shown that the stratum corneum of the volar fingertips is thinner in women than in men [16]. The lower epidermal insulation may facilitate

heat transfer from deeper, perfused tissues to the contact surface, thereby increasing the sensitivity of TP to changes in FBF. The positive association between BMI and TP is unlikely to reflect a direct effect of localized adiposity at the fingertip. If present, greater local adipose tissue would be expected to increase thermal insulation and potentially reduce, rather than increase, heat transfer to the cooled surface. Therefore, BMI may more plausibly serve as an indirect anthropometric marker of body size, finger morphology, tissue mass, or effective contact area, all of which influence thermal exchange during finger-surface contact [17]. The inclusion of random-intercept and random-slope terms allowed for accounting for both baseline differences between subjects and subject-specific variability in the TP-FBF relationship, leading to a more accurate and flexible estimation of the FBF effect. The persistence of a significant FBF effect after adjustment for covariates confirms its role as an independent predictor of thermal power. Moreover, from a methodological standpoint, these findings highlight the importance of controlling individual and environmental variables when interpreting thermal measurements. Although thermal power is strongly influenced by blood perfusion, it also depends on boundary conditions and tissue-specific properties. Therefore, standardized acquisition protocols and appropriate statistical modeling are essential to ensure robustness and comparability.

In this study, some limitations should be considered. The sample size was relatively small (n = 20), and only healthy subjects were included. In addition, although contact force and temperature were carefully controlled, residual variability related to finger positioning, effective contact area, and initial skin temperature cannot be ruled out.

5. Conclusion

The present study provides preliminary evidence supporting the feasibility and physiological relevance of a thermal power-based approach for assessing digital vascular response to cold. Under controlled experimental conditions, the proposed portable device detected a clear increase in thermal power during local cooling and showed improved repeatability when the cold stimulus was applied. At the same time, local cooling induced a measurable reduction in finger blood flow, confirming that the experimental protocol elicited a physiologically meaningful vascular response. The significant association between thermal power and finger blood flow measured by strain-gauge plethysmography provides preliminary support for the interpretation of TFM-derived thermal power as an indirect measure of digital blood perfusion.

These findings suggest that the TFM may represent a promising, non-invasive, and portable tool for the functional assessment of digital vascular response to cold. Its potential applicability in occupational health surveillance is particularly relevant, as current objective methods for evaluating vibration-induced vascular disorders are often limited by technical complexity, test duration, and poor portability. This study should be considered as an initial validation step. Further studies are needed in larger populations and, mainly, in subjects affected by primary or secondary Raynaud's phenomenon, VWF, or other digital vascular disorders, in order to (i) define diagnostic TFM thresholds, (ii) assess the sensitivity, specificity, and predictive value of the TFM method, (iii) evaluate its reproducibility in clinical and workplace settings, and (iv) ascertain the contribution of the TFM method to the health surveillance of workers exposed to hand-transmitted vibration.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Politecnico di Milano (authorization no. 41/2025; date of approval: 19 May 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Declaration of Interest: The authors declare no conflict of interest.

Author Contribution Statement: M.B., M.M., and A. T. contributed to the design of the study. C.M. and M.T. designed and developed the device. P.B. and M.M. contributed to the implementation of the experimental tests. C.M.,

P.B., and M.B. contributed to the analysis and interpretation of the results. C.M., P.B., and M.M. contributed to the writing of the manuscript. M.T., A. T., and M.B. critically revised the manuscript. All authors read and approved the final version of the manuscript.

References

1. Nilsson T, Wahlström J, Burström L. Hand-arm vibration and the risk of vascular and neurological diseases-A systematic review and meta-analysis. *PLoS One.* 2017;12(7):e0180795. Doi: 10.1371/journal.pone.0180795
2. Taylor W, Wasserman D, Behrens V, Reynolds D, Samueloff S. Effect of the air hammer on the hands of stonecutters. The limestone quarries of Bedford, Indiana, revisited. *Br J Ind Med.* 1984;41(3):289-295. Doi: 10.1136/oem.41.3.289
3. Bovenzi M. Vibration-induced white finger and cold response of digital arterial vessels in occupational groups with various patterns of exposure to hand-transmitted vibration. *Scand J Work Environ Health*. 1998;24(2):138-144. Doi: 10.5271/sjweh.291
4. Tekavec E, Nilsson T, Dahlin LB, et al. Serum levels of biomarkers related to severity staging of Raynaud's phenomenon, neurosensory manifestations, and vibration exposure in patients with hand-arm vibration injury. *Sci Rep.* 2024;14(1):18128. Doi: 10.1038/s41598-024-68846-1
5. Bovenzi M. A longitudinal study of vibration white finger, cold response of digital arteries, and measures of daily vibration exposure. *Int Arch Occup Environ Health.* 2010;83(3):259-272. Doi: 10.1007/s00420-009-0461-2.
6. Bovenzi M, Tarabini M. Relation of digital arterial dysfunction to alternative frequency weightings of hand-transmitted vibration. *Ind Health.* 2024;62(1):32-38. Doi: 10.2486/indhealth.2023-0023
7. Mahbub M, Harada N. Review of different quantification methods for the diagnosis of digital vascular abnormalities in hand-arm vibration syndrome. *J Occup Health.* 2011;53(4):241-249. Doi: 10.1539/joh.10-0030-ra.
8. Lindsell CJ, Griffin MJ. Normative data for vascular and neurological tests of the hand-arm vibration syndrome. *Int Arch Occup Environ Health.* 2002;75(1-2):43-54. Doi: 10.1007/s004200100277
9. Matikainen E, Leinonen H, Juntunen J, Seppäläinen AM. The effect of exposure to high and low frequency hand-arm vibration on finger systolic pressure. *Eur J Appl Physiol Occup Physiol.* 1987;56(4):440-443. Doi: 10.1007/BF00417772.
10. Ye Y, Mauro M, Bovenzi M, Griffin MJ. Reduction in finger blood flow induced by hand-transmitted vibration: effect of hand elevation. *Int Arch Occup Environ Health.* 2015;88(7):981-992. Doi: 10.1007/s00420-015-1027-0
11. Ye Y, Mauro M, Bovenzi M, Griffin MJ. Association between vasoconstriction during and following exposure to hand-transmitted vibration. *Int Arch Occup Environ Health.* 2014;87(1):41-49. Doi: 10.1007/s00420-012-0836-7
12. Jay O, Havenith G. Differences in finger skin contact cooling response between an arterial occlusion and a vasodilated condition. *J Appl Physiol (1985).* 2006;100(5):1596-1601. Doi: 10.1152/japplphysiol.00760.2005.
13. Greenfield AD, Whitney RJ, Mowbray JF. Methods for the investigation of peripheral blood flow. *Br Med Bull.* 1963;19:101-109. Doi: 10.1093/oxfordjournals.bmb.a070026.
14. Chen F, Nilsson H, Holmér I. Finger cooling by contact with cold aluminium surfaces—effects of pressure, mass and whole body thermal balance. Eur *J Appl Physiol Occup Physiol.* 1994;69(1):55-60. Doi: 10.1007/BF00867928.
15. Bland JM, Altman DG. Measurement error. *BMJ.* 1996;312(7047):1654. Doi: 10.1136/bmj.312.7047.1654
16. Fruhstorfer H, Abel U, Garthe CD, Knüttel A. Thickness of the stratum corneum of the volar fingertips. *Clin Anat.* 2000;13(6):429-433. Doi: 10.1002/1098-2353(2000)13:6<429::AID-CA6>3.0.CO;2-5
17. Jay O, Havenith G. Finger skin cooling on contact with cold materials: an investigation of male and female responses during short-term exposures with a view on hand and finger size. *Eur J Appl Physiol.* 2004;93(1-2):1-8. Doi: 10.1007/s00421-004-1146-x

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