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Impact of Physical (In)Activity on Carotid-Femoral PWV and Central Blood Pressure in Young and Middle-Aged Adults: A Pilot Study using ARTSENS Plus

Ganapathy Jaganathan
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
ee21d029@smail.iitm.ac.in

Rahul Manoj
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
rahul_manoj@smail.iitm.ac.in

Raj Kiran V
Healthcare Technology Innovation Centre (HTIC), IIT Madras
Chennai, India
ee15d020@smail.iitm.ac.in

P. M. Nabeel
Healthcare Technology Innovation Centre (HTIC), IIT Madras
Chennai, India
nabeel@htic.iitm.ac.in

Jayaraj Joseph
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
jayaraj@ee.iitm.ac.in

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Abstract— **Carotid-femoral pulse wave velocity (cfPWV) and central blood pressure (BP) are prognostic stiffness markers for assessing vascular health. In this study, a group of young ($20 \leq age < 40$) to middle-aged ($40 \leq age < 60$) participants with minimal cardiovascular risk were examined to determine the impact of physical (in)activity on central BP and cfPWV. This in-vivo study was conducted on 97 healthy participants (Mean age: 34) . All participants completed a detailed lifestyle and medical history questionnaire, which included information on their lifestyle and physical activity. An in-house developed A-mode ultrasound device, ARTSENS Plus was used to measure, central BP (from the carotid artery) and cfPWV. There was no significant difference in central BP and cfPWV between physically active and inactive young adults ($p > 0.05$). Although cfPWV in middle-aged adults increased by 26% in females and 10% in males between active and inactive populations, the observation was not statistically significant ($p = 0.14$ in males and $p = 0.11$ in females). The difference in carotid pulse pressure between physically active and inactive middle-aged adults was statistically significant ($p \leq 0.05$). Results from this study will eventually cast new light on the importance of physical (in)activity among young and middle-aged populations.**

Keywords—Carotid-femoral pulse wave velocity, central blood pressure, stiffness markers, A-mode ultrasound, carotid artery.

I. INTRODUCTION

Vascular Aging (VA) is the deterioration of arterial vessel wall structure and function with aging, which is accelerated due to cardiovascular risk factors. This deterioration in vascular structure leads to cardiovascular diseases (CVD), which include heart attack, stroke, and end-organ damage [1]. Primordial and primary care intervention strategies are considered to be crucial for preventing CVD. Large arterial stiffness is a biomarker for vascular aging and a risk factor for cardiovascular morbidity and mortality [2]. Increasing age coincides with a loss of elasticity in large elastic arteries. This phenomenon is mediated by alterations in the arterial wall composition and smooth muscle cell function modifications, resulting in enhanced contractility of vascular smooth muscle cells [22]. The two extremes of the VA distribution are Early Vascular Aging (EVA) and Supernormal Vascular Aging (SUPERNOVA), which denote abnormally high and low large arterial stiffness, respectively, for their age and sex. While SUPERNOVA individuals may maintain elastic blood vessels as they age, which is protective against CVD, EVA individuals are more likely to acquire arterial stiffness and CVD at a younger age [3]. Large arterial stiffness is clinically measured in terms of cfPWV and central blood pressure [4],[3]. Carotid blood pressure is a surrogate for central blood pressure as the carotid artery directly branches from the aorta [5]. As assessed by cfPWV, arterial stiffness has become increasingly recognized as an important marker of cardiovascular well-being beyond traditional risk factors such as blood pressure. This is because cfPWV provides valuable information about the advancement of blood pressure issues and the vulnerability to organ damage, which is especially advantageous for individuals with borderline hypertension or uncertain medical conditions [23]. Large artery vessels get deranged over one's life course trajectory. Studies hypothesized that performing suitable timely intervention can achieve SUPERNOVA [1], and conducting physical activity is one of the interventions.

Physical activity positively impacts large arterial stiffness and minimizes the morbidity and mortality associated with CVD [6]. Within this research, physical activity refers to any bodily movement mediated by skeletal muscles that increases energy expenditure. Examples include walking, cycling, and engaging in sports. According to Consensus Physical Activity Guidelines for Asian Indians, a minimum of 300 minutes of moderate-intensity physical activity throughout the week is recommended for adults [7]. Technology is

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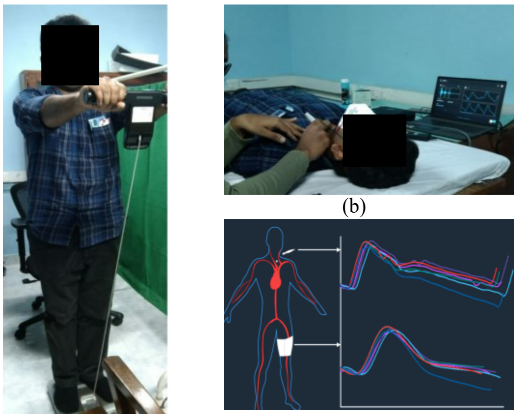
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(b)

(a) (c)

Fig.1. (a) Body Composition Monitor. (b) An operator performs central blood pressure and cfPWV measurement. (c) Measurement page showing the recorded carotid diameter and femoral pulse waveform

required to monitor the impact of interventions on large arterial stiffness markers. We have developed the ARTSENS Plus [8], an A-mode ultrasound-based device that is simple to use and deploy in the field which can measure both central blood pressure and cfPWV in a single test is used to examine the effects of physical (in)activity on large arterial stiffness markers. The study and device details are elaborated in Section II, followed by study results discussing the impact of (in)activity in large arterial stiffness indicators and the limitations and future scope of the study in Section III.

II. MATERIALS AND METHODS

A. *Study Population*

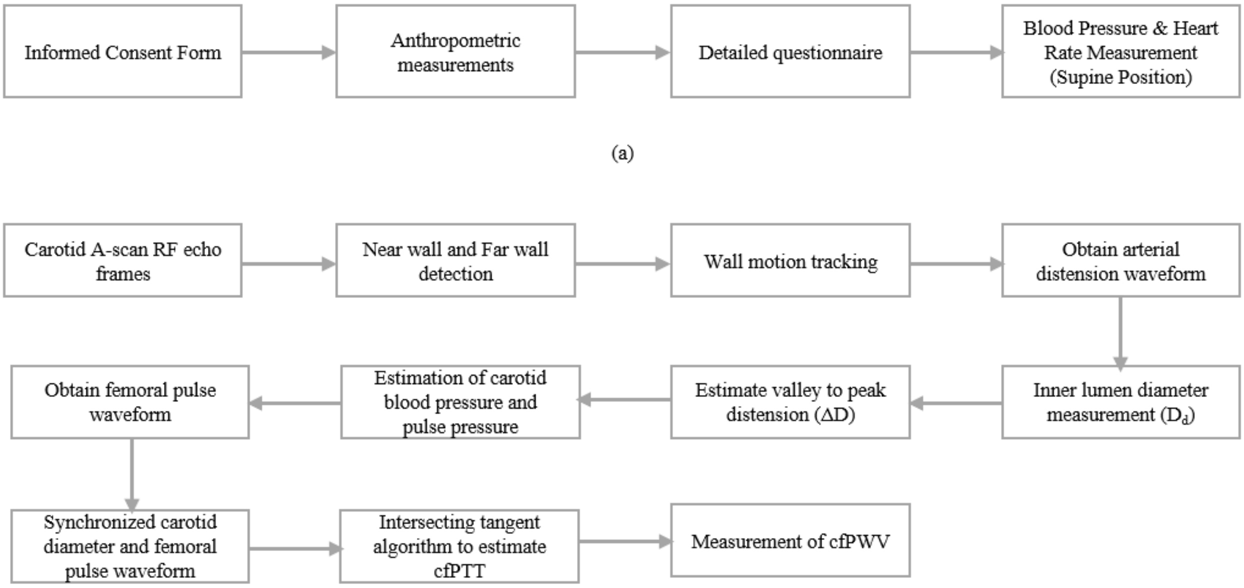
The study was conducted as a cross-sectional survey at IIT Madras, Tamil Nadu, India, consisting of 97 healthy participants. Since the study objective is to investigate the impact on central blood pressure and cfPWV in active and inactive males and females among young ($20 \leq$ age < 40) and middle-aged adults ($40 \leq$ age < 60) [9], adults who engage in moderate to strenuous physical exercise for at least 300 minutes per week were considered active, while those who do not were considered inactive [7]. A written informed consent form was obtained from all participants before the measurement. This study was examined and approved by the IIT Madras Institute review boards (IEC/2021-01/JJ/07) and was conducted in accordance with the Helsinki Declaration 1975, revised in 2013.

B. *Study Protocol*

Participants were instructed to refrain from consuming dietary goods known to alter stiffness (e.g., caffeinated drinks) for at least 4 hours before the measurement. Weight and height were measured and body mass index was calculated upon arrival (Fig.1.(a)). A systematic questionnaire was used to collect data on risk variables which include age, cigarette usage, alcohol use, current medication for hypertension and diabetes, and physical activity details. Participants were requested to be supine with a headrest for at least 5 minutes**.** All participants had their blood pressure measured on the left upper arm. The reference brachial pressure measured by the cuff assessed on the patient in supine position. Supine position is generally preferred for calibrating carotid blood pressure estimates from brachial measurements because gravity's influence on blood pressure is minimized, reducing its impact on the brachial reading used for estimation. Calibration remains necessary to account for inherent differences between the arteries, but the supine position offers a more reliable starting point due to potentially more consistent diastolic pressure throughout the arterial system in this position [25]. The concise overview of the study plan is outlined in Fig.2.(a).

C. *Data collection*

The ARTSENS Plus device utilized in this study has the following components: (a) a brachial pressure cuff, (b) a



(a)

(b)

Fig.2. (a) Study Plan and (b) ARTSENS Plus Software Architecture for estimation of central blood pressure and cfPWV

custom-made A-mode ultrasound transducer with a central frequency of 10 MHz, and (c) a thigh pulse detector (femoral cuff). The ultrasonic hardware circuit employed in this study is the most recent version of the ARTSENS® technology [10]. The device has done the following measurements: (a) measures brachial pressure, (b) measures continuous beat-to-beat carotid diameter waveform, end-diastolic lumen diameter (Dd), and distension (ΔD), and (c) acquires femoral pulse waveform (Fig.1.(c)).

The operator affixed the brachial and femoral pressure cuff on the participant. The brachial blood pressure and heart rate were recorded from the left arm. The left common carotid artery was identified by palpation. The ultrasound probe was positioned and oriented on the participant's neck in the supine position. To estimate the arterial diameter, the probe must be placed normally to the pulsating artery to capture the sharpest RF echoes. (Fig.1.(b)). The thigh pulse detector was inflated, and femoral pulse waveforms were obtained. The distance from the carotid to the femoral artery was measured to estimate cfPWV.

D. Data Preparation and Processing

Application-specific measurement software for ARTSENS Plus was developed using the virtual instrument platform (LabVIEW 2015, 32-bit, National Instruments Co., Austin, Texas, United States). The application incorporates a patient data management system and intelligent signal processing algorithms to automatically evaluate arterial dimensions and stiffness [11], [26]. The simplified representation of the software architecture is illustrated in Fig.2.(b). The ARTSENS Plus integrated oscillometric module with pressure cuff automatically measured brachial pressure. The ultrasound probe obtained A-mode scans of the common carotid artery [12]. Obtained RF echoes are converted to diameter waveform using a validated algorithm [13]. The obtained diameter waveform was converted to carotid pressure waveform, which gives carotid systolic and diastolic blood pressure (cSBP, cDBP) and carotid pulse pressure (cPP) using an exponential relationship between pressure and arterial cross-sectional area [14]. The pressure waveform was calibrated using diastolic blood pressure and mean arterial pressure acquired from an oscillometric BP device at the brachial artery.

The pulse detector wrapped around the thigh was inflated to record high-fidelity pulse waves from the femoral artery without perturbing the blood flow. Carotid to femoral pulse transit time (cfPTT) and cfPWV were calculated using the synchronized carotid diameter and femoral pulse waves. The 'intersecting tangent algorithm' [15] gives a valid

TABLE I. CHARACTERISTICS OF STUDY POPULATION (N = 97)

Parameter	Mean ± SD	Range
Age (Years)	34 ± 12	20 - 59
Gender (Male/Female)	55/42	-
Height (cm)	167 ± 11	142 - 194
Weight (kg)	70 ± 16	40 - 123
Brachial SBP (mmHg)	116 ± 13	90 - 149
Brachial DBP (mmHg)	75 ± 8	58 - 100
Heart rate (BPM)	74 ± 11	47 - 98
Carotid SBP (mmHg)	108 ± 13	83 - 142
Carotid DBP (mmHg)	75 ± 8	58 - 100
Carotid PP (mmHg)	32 ± 8	18 - 52
D_d (mm)	6 ± 0.75	4 - 8
ΔD (mm)	0.46 ± 0.13	0.23 – 0.86
cfPWV (m/s)	6.19 ± 1.91	3.68 - 13.04

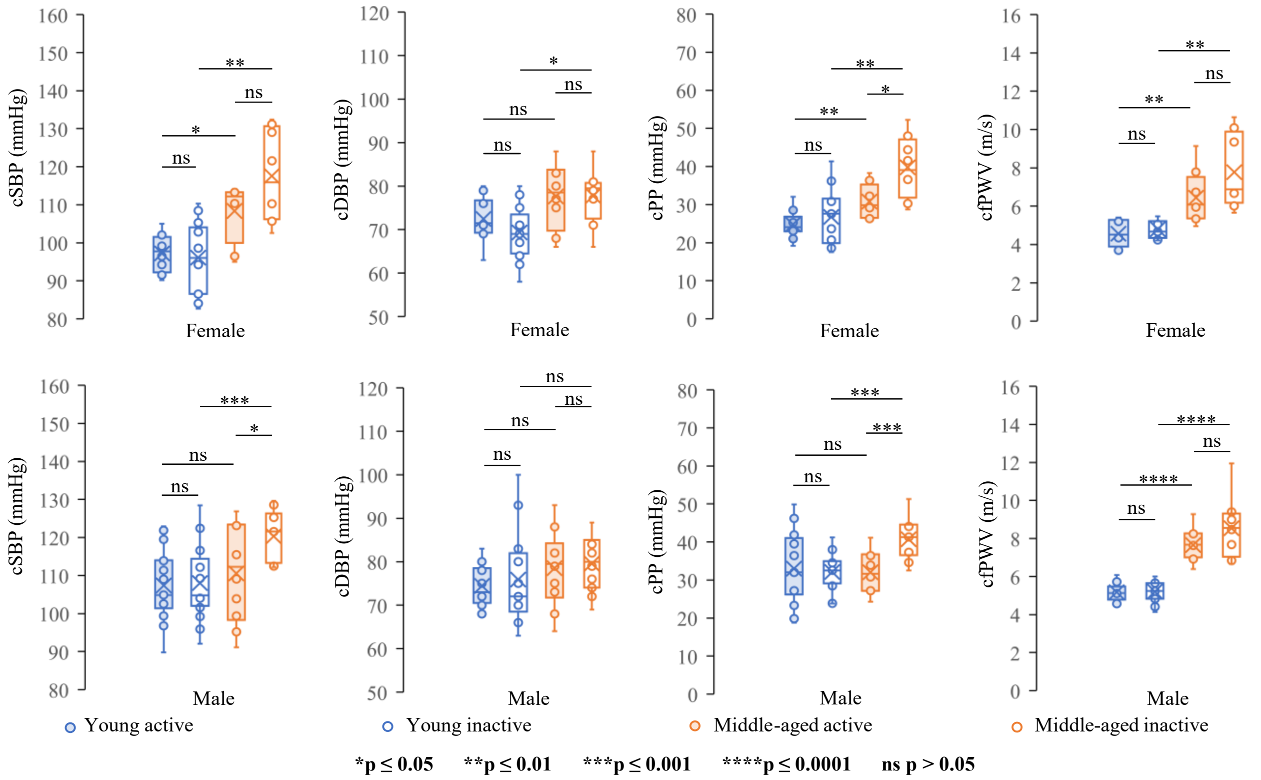


Fig.3. Box-and-Whisker plots illustrating the measured indicators distribution among different groups in female and male population and indicating

TABLE II. VALUES OF MEASURED INDICATORS AMONG DIFFERENT GROUPS (N = 97)

Indicators	**Female (N = 42)**				**Male (N = 55)**			
	Young Active (N = 12)	**Young Inactive (N = 13)**	**Middle-Aged Active (N = 9)**	**Middle-Aged Inactive (N = 8)**	**Young Active (N = 17)**	**Young Inactive (N = 17)**	**Middle-Aged Active (N = 10)**	**Middle-Aged Inactive (N = 11)**
cSBP(mmHg)	97 ± 5	95 ± 9	108 ± 8	118 ± 12	107 ± 9	108 ± 10	111 ± 13	120 ± 7
cDBP(mmHg)	72 ± 5	70 ± 6	78 ± 8	78 ± 7	74 ± 5	76 ± 10	79 ± 9	80 ± 6
cPP(mmHg)	25 ± 3	26 ± 6	31 ± 5	40 ± 8	33 ± 9	32 ± 5	32 ± 5	41 ± 5
cfPWV (m/s)	4.6 ± 0.7	4.8 ± 0.5	6.4 ± 1.4	7.8 ± 1.9	5.2 ± 0.5	5.2 ± 0.5	7.7 ± 0.8	8.5 ± 1.5

All values are indicated in Mean ± Standard Deviation

measurement of cfPTT, which was essential for calculating cfPWV.

E. Statistical Analysis

Results were reported as mean ± standard deviation or minimum-to-maximum range. For each indicator, box and whisker plots were plotted. The means of the indicator among different groups were compared using the student's t-test. A p-value of 0.05 or below was regarded as statistically significant.

III. RESULTS AND DISCUSSIONS

A. Participants Demography

TABLE I summarizes the descriptive features of the recruited study population. Among total population, young active groups constitutes 30%, young inactive 30%, middle-aged active 20% and middle-aged inactive 20%. The 97 people who enrolled for the vascular screening study participated and carotid blood pressure and cfPWV measurements were successfully obtained (TABLE I). There were 27 active males, 28 inactive males, 21 active females, and 21 inactive females.

B. Measurement Reliability

The operator completed the whole study protocol in 5-10 minutes. Both the measurement procedure and the palpation was done by the same expert operator. Raw A-scan RF frames and femoral pulse waves had signal-to-noise ratios greater than 25 and 30 dB, respectively, ensuring high signal fidelity. The beat-to-beat repeatability of measuring Dd was < 5.8%, whereas the repeatability in ΔD was < 3.8 %. The carotid diameter and femoral pulse waveforms were acquired at 250 Hz and oversampled to 1000 Hz using a cubic spline interpolation approach. As a result, these waveforms had a temporal resolution of 1 ms. The cfPWV had a beat-to-beat repeatability < 5.5%. ARTSENS Plus device was validated against the reference gold standard device SphygmoCor XCEL (AtCor Medical, Sydney, Australia). Regarding cfPTT and cfPWV, the average deviations were 3.97 and 4.06%, respectively. The highest variation measured in cfPWV from the reference was 0.77 m/s [8].

C. Effect of stiffness markers on Physical (in)activity

TABLE II summarizes the average values of cSBP, cDBP, cPP, and cfPWV for the population based on age-matched young active and inactive groups ($p > 0.05$) and age-matched middle-aged active and inactive groups ($p > 0.05$). As observed from Fig.3., the magnitude increase in cSBP was prominent in comparison to cDBP due to aging; this is due to the fact that the magnitude increase of systolic blood pressure is higher in comparison to diastolic blood pressure over one's life course trajectory [16]. However, there was a significant increase in the mean cSBP value from the young inactive to middle-aged inactive male population ($p \leq 0.0001$), and an insignificant difference was observed in the mean cSBP value among the young to middle-aged active male population ($p > 0.05$). In the female population, there was a significant increase in mean cSBP value in both young active to middle-aged active ($p \leq 0.05$) and in young inactive to middle-aged inactive ($p \leq 0.01$) groups. Also, the mean values of cPP increased in the female middle-aged population compared to the female young population both in active and inactive groups. In the male population, the mean value of cPP increased in middle-aged inactive groups compared to the young inactive group, and there was a decrease in cPP mean value in the middle-aged active group in comparison to the young active group. From TABLE II, the female population shows a more prominent increase in cPP mean values due to aging (24% increase in the middle-aged active & 54% increase in the middle-aged inactive group), and this result was in line with the previous study [17]. Since the mean value of cSBP prominently increased higher compared to cDBP over age, the mean value of cPP also increased prominently over age, and it was significant in the male, middle-aged inactive group ($p \leq 0.0001$), in the female middle-aged inactive group ($p \leq 0.01$) and in the female middle-aged active group ($p \leq 0.01$).

From Fig.3., it was evident that the cPP mean value showed a significant increase in the middle-aged inactive group compared to the middle-aged active group ($p \leq 0.0001$ in the male population and $p \leq 0.05$ in the female population), and cSBP mean value shows a significant increase in a middle-aged inactive group compared to middle-aged active group ($p \leq 0.05$). Epidemiologic research shows that physical activity is linked to decreased blood pressure at particular times [6]. As depicted in Fig.3, among the young active and inactive groups, there existed insignificant ($p > 0.05$) differences in mean values of all the stiffness markers. The extent of arterial wall remodeling due to structural impairments is minimal in the young group, as compared to the middle-aged group [18]. The physical (in) activity-related trends in cPP reported in similar studies also coincided with the observed results [19].

The range of cfPWV for young and middle-aged groups obtained in this study was concurrent with the previous study [4]. cfPWV also shows an increasing trend in mean values due to aging, which was in accordance with the previous study [4]. Contrary to the cPP mean value, cfPWV shows insignificant differences among middle-aged active and inactive groups in both the male and female populations ($p > 0.05$). The mean value of cfPWV increased by 22% and 10% in the middle-aged inactive group compared to the middle-aged active group in the female and male populations, respectively. The broader dispersion in cfPWV among the middle-aged groups was predominately due to deviation in vascular aging trajectories from young to middle age under the influence of various risk factors [20]. Recent studies on using cfPWV to measure physical (in)activity had reported significant increase ($p \leq 0.05$) in cfPWV due to inactivity, as opposed to the results observed in this study [21]. These differences may be attributed to the demographics of the participants chosen.

Physical activity holds the potential to enhance arterial health through various pathways, both direct and indirect. Directly, it could lead to enhancements in microvascular structure and function, resulting in reduced blood pressure and consequent mitigation of arterial stiffness. Moreover, exercise may prompt changes in body composition, decreasing adipose tissue and potentially ameliorating metabolic profiles, thereby indirectly contributing to improved arterial health [24]. Although our study did not yield statistically significant findings for cfPWV, notably among younger adults, the discernible trends, particularly within the middle-aged cohort, support this proposition. This suggests that physical activity may exert a more pronounced influence on sustaining arterial health with advancing age. Nonetheless, larger-scale studies encompassing a more extensive participant pool must conclusively delineate these associations. This underscores the imperative for forthcoming research to investigate optimal strategies for harnessing the benefits of physical activity on arterial health. Subsequent studies could identify the most efficacious exercise modalities, whether prioritizing aerobic activities, resistance training, or a blend of both. Additionally, examining optimal exercise intensity and duration tailored to distinct age brackets would be instrumental in devising targeted physical activity regimens to optimize their positive impact on arterial stiffness and cardiovascular well-being.

D. Limitations and Future scope

Advancements in computer vision and machine learning are enabling powerful computerized recognition, segmentation, and detection methods, revolutionizing image-based analysis [30-33]. This trend emphasizes the need for further development in automated ultrasound technologies. While our study utilized A-mode ultrasound for measuring carotid blood pressure and regional arterial stiffness without image analysis, future research integrating automation with A-mode techniques could offer significant advantages in terms of efficiency, accuracy, and consistency of measurements. Our study acknowledges the limitation of a small sample size, particularly within the middle-aged cohort, which may hinder the applicability of our results to a broader population. A larger sample size would enable more rigorous statistical analysis and potentially uncover significant findings concerning cfPWV in middle-aged individuals. Diet, stress levels, and genetic predispositions could influence our outcomes. To strengthen our observations and improve generalizability, future studies require more extensive and more diverse participant cohorts. Moreover, integrating assessments of these confounding factors, such as standardized dietary assessments, stress evaluations, and potentially genetic analysis, would provide a more comprehensive understanding of the interrelationship between physical activity, arterial stiffness, and cardiovascular health. To address these limitations, forthcoming research could entail collaborations with other institutions to enhance sample size and participant diversity. Multi-center studies and longitudinal approaches tracking participants over time would offer valuable insights. Through meticulous control of potential confounders and utilization of larger, more diverse samples, future investigations can advance our understanding of the impact of physical activity on arterial health across varying age demographics. Studies are in progress to investigate the effects of large artery stiffening on physical (in)activity in larger cohorts among diverse groups. Local stiffness markers had recently emerged as prognostic arterial stiffness indices in diverse populations [15], [27-29]. Studies in this line are in the pipeline to investigate the association of local stiffness parameters with age and physical (in)activity.

IV. CONCLUSION

The impact of physical (in)activity on cfPWV and central blood pressure in young and middle-aged adults was studied using an in-house developed A-mode ultrasound device, ARTSENS Plus. Carotid pulse pressure significantly increases mean values in middle-aged adults among active and inactive groups. Large arterial stiffness indicators in young adults show no significant change among active and inactive groups. There was a broad range of dispersion on cfPWV in middle-aged adults, and a substantial increase in mean values due to aging was found, but no significant increase was found among active and inactive groups. An extensive study on larger cohorts is in progress, which includes young, middle-aged, and old-aged adults to assess the impact of physical (in)activity on vascular health among active and inactive populations.

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