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Effect of Resistance Training in Water with Blood Flow Restriction on Heart Rate Variability, Functional Capacity, and Pain in Postmenopausal Women with Knee Osteoarthritis

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Abstract

Background: Resistance training has been suggested as a potential treatment for knee osteoarthritis but may be harmful to people with chronic pain. The fear of this pain and chronic inflammation leads to disorder in the automatic nervous system and reduces activity, heart rate variability, and cardiovascular fitness. This study aimed to investigate the effect of a combination of aquatic resistance training and blood flow restriction on heart rate variability, functional capacity, and pain in postmenopausal women with knee osteoarthritis.

Methods: Thirty-eight postmenopausal women with grade 2 and 3 arthritis were randomly assigned to three groups by drawing lots: water resistance training (AQE, *n*=13), water resistance training with BFR (BFR+AQE, *n*=14), and control group (*n*=11). One week before the beginning and 48 hours after the last session of the intervention program, heart rate variability, functional capacity, and subjects' pain were evaluated. RMSSD, SDNN, LF, and HF were measured at rest and while walking to evaluate heart rate variability. Functional capacity was measured by assessing functions, including standing on a chair, getting up and walking, walking speed, two minutes of walking, and dynamic balance.
The study's protocol was also registered in the Iranian Registry of Clinical Trials (registration No.: IRCT20240911063005N1).

Results: According to the results, after the intervention period, there was a significant increase in the HFpeak index (P=0.049) and a significant increase in the low-frequency/high-frequency walking ratio (P=0.015) in the AQE group, a decrease in standing time on a chair (improvement) in both exercise groups (P=0.002), a significant increase in the dynamic balance in the AQE BFR exercise group (P=0.004), and a significant decrease in the pain index in the AQE exercise group (P=0.009). No significant difference was observed between the exercise groups in the other measured indicators.

Conclusion: Our results suggest that resistance training reduces stress, inflammation, and pain caused by physical problems through increased parasympathetic and vagal activity. Increased heart rate variability indicates cardiovascular flexibility, adaptation to exercise, and improved mental health (e.g., reduced anxiety and pain). This, in turn, increases mobility and physical activity in these individuals and can prevent the onset or development of disease by increasing HF and the LF/HFw ratio. Combining aquatic resistance training and BFR is an innovative and practical approach to improving the quality of life of people with knee osteoarthritis. Also, improvement in HRV after non-pharmacological interventions (e.g., resistance exercise, aerobics, tai chi, meditation) can indicate the effectiveness of treatment. This helps clinicians adopt more personalized approaches.

Keywords: Water resistance training, Resistance training in water with blood flow restriction, Heart rate variability, Functional capacity, Knee osteoarthritis, Menopause

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Introduction

Osteoarthritis (OA) is a chronic, progressive disease characterized by abnormalities in the cartilage, leading to bone-on-bone contact (1). It is a major cause of disability in older adults and, with increasing life expectancy, has become a significant public health challenge (2, 3). OA can impair independence in self-care, affect daily activities, such as knee flexion, sitting, and standing from a chair, and reduce the quality of life of affected individuals (1). The prevalence of OA is higher in women and older adults (4), with the risk in women increasing significantly after menopause due to reduced estrogen levels (5, 6). As people age, the exercise intensity required for muscle hypertrophy, coupled with increased stress on joints, can lead to greater pain (7-9) and reduced adherence to physical activity (7). Fear of pain or worsening symptoms may discourage individuals with OA from engaging in beneficial exercise (10, 11), resulting in decreased cardiorespiratory fitness (11) and increased cardiovascular risk (10). A non-invasive method to assess cardiovascular risk due to physical inactivity in individuals with knee osteoarthritis (KOA) is assessing heart rate variability (HRV). Reduced HRV directly predicts cardiovascular risk and all-cause mortality (12). Patients with knee osteoarthritis often experience kinesiophobia (fear of movement-induced pain), which triggers chronic stress responses through prolonged sympathetic nervous system (SNS) activation (13). Dominant SNS activity reduces heart rate variability (HRV), while controlled slow breathing may induce respiratory sinus arrhythmia, alleviating pain and SNS responses (13). This autonomic dysfunction correlates with OA-related pain and perceived stress (14). Early-stage OA patients exhibit deficient parasympathetic nervous system (PNS) activity. PNS activation via cholinergic pathways demonstrates anti-inflammatory effects that protect the individual against OA progression (14). Consequently, insufficient PNS activity may represent a significant risk factor for OA development and severity (14). The evidence highlights the critical balance between sympathetic and parasympathetic systems in OA pathophysiology. Aerobic and high-intensity interval resistance exercises can enhance cardiorespiratory function by suppressing sympathetic nervous system activity and stimulating parasympathetic activity. Specifically, improved autonomic nervous system function contributes to increased HRV (15, 16). Rapid restoration of HRV after blood flow restriction (BFR) training (17), improved autonomic nervous system function through resistance training (16), and vascular function improvement via aquatic exercise (18) collectively create favorable physiological conditions for training adaptation while reducing cardiovascular risk (17).

On the other hand, key symptoms of KOA include muscle weakness, joint instability, stiffness, reduced functional strength, and pain (7, 9, 19). Pain, the primary symptom of OA (2), is often the first clinical sign prompting individuals to seek medical care (20). Pain correlates with reduced functional activity and muscle strength (1). Consequently, preserving lower limb muscle strength and hypertrophy, particularly in the quadriceps, is considered the first line of treatment for KOA patients (7, 21). The International Association of Osteoarthritis Research (OARSI) recommends high-intensity strength training aimed at improving muscle strength and volume to slow KOA progression (8, 22), relieve pain, reduce stiffness, improve muscle function, and enhance lower limb shock absorption during walking (23). The American College of Sports Medicine (ACSM) suggests resistance training loads of 60–70% of one repetition maximum (1RM) for strength and 70–85% of 1RM for hypertrophy (24). However, this intensity may exacerbate symptoms in individuals already experiencing knee pain (25). Thus, alternative strategies to make traditional resistance training more tolerable and effective while addressing cardiovascular health risks in KOA patients (26) include aquatic resistance exercises (AQE) and incorporating BFR.

Aquatic therapy is a weight-bearing-free exercise method that minimizes the risk of joint damage from excessive loading (27, 28). The unique physical properties of water—buoyancy, hydrostatic pressure, viscosity, and thermodynamics—create distinct physiological (e.g., venous return facilitation, muscle fatigue relief, and edema reduction) and biomechanical (e.g., joint protection due to reduced weight-bearing and increased muscle activity against water resistance) benefits during exercise (29).

BFR, another technique for strengthening muscles in KOA patients, is a viable alternative for older individuals who cannot tolerate high-resistance exercises due to comorbidities or joint stress (30). BFR involves applying a cuff to create temporary ischemia in targeted tissues while maintaining blood inflow (9). This ischemia stimulates angiogenesis and promotes biochemical and physiological changes such as muscle growth (8, 9, 19). Given the benefits of resistance training, BFR, and aquatic exercise for KOA patients and the importance of evaluating cardiovascular risks associated with fear of movement, this study aims to compare the effects of aquatic resistance training with and without BFR on HRV, functional indices, and pain in postmenopausal women with KOA.

Methods

Postmenopausal women with grade 2 and 3 osteoarthritis (based on the radiological grading scale of osteoarthritis described by Kellgren-Lawrence from radiographs of the knee of individuals) were identified through patient records in a rheumatology clinic and invited to participate in the study. The participants had a mean age of 54.68 ± 6.54 years, mean weight of 71.62 ± 11.96 kg, mean BMI of 29.90 ± 4.43 kg/m², and mean age at menopause of 39.7 ± 3.59 years. After the eligible participants received a complete explanation of the procedures and were informed of the risks and benefits of the study, they signed an informed consent form based on the Declaration of Helsinki. Inclusion criteria included not using non-steroidal anti-inflammatory drugs in the past 3 months and no corticosteroid injections in the past 6 months. Exclusion criteria were missing more than three non-consecutive training sessions and experiencing injuries during training. Before the participants entered the study, baseline anthropometry (height, weight, and body mass index), BFR pressure (by measuring thigh circumference, diastolic and systolic pressure, and inserting into the arterial occlusion point formula), HRV, functional capacity, and pain index were assessed in at least three visits to the laboratory. The participants were then randomly assigned three groups by drawing lots: (a) AQE ($n = 13$), (b) AQE + BFR ($n = 14$), and (c) control group ($n = 11$) and performed the exercises in three sessions per week for eight weeks (a total of 24 sessions). The control group received no intervention. All participants were asked not to participate in any other physical activity program during the study but to maintain their current activity and dietary habits. The study was registered with the Ethics Committee of Birjand University with the code IR.BIRJAND.REC.1402.016. The study's protocol was also registered in the Iranian Registry of Clinical Trials (registration No.: IRCT20240911063005N1).

Heart Rate Variability Assessment

Heart rate variability was assessed at rest and during walking using a Polar (H_{10}) sensor placed on the sternum. Participants were placed in a supine position in a quiet room (temperature 22–24 degrees Celsius) and instructed to breathe normally, remain calm, and not talk or fidget during the assessment. After 10 minutes, heart rate variability was recorded for 5 minutes at a sampling frequency of 1000 Hz (31). Heart rate variability was also measured during walking simultaneously with the 2-minute walk test. After data recording, information on time-domain variables, root mean square of successive differences of RR intervals (RMSSD), standard deviation of regular RR intervals (SDNN); and frequency-domain variables, low-frequency waves (LF) and high-frequency waves (HF) were obtained from the Elite HRV software (32).

Functional Capacity Assessment

Chair stand test: Participants were instructed to stand up from and sit down on a 43-cm-high chair five times in a row (33).

Timed up and go test: Participants were asked to stand up as quickly as possible from a 43 cm high chair, walk 3 meters along a straight line, turn around, return to the chair, and sit down (33).

Walking speed test (6 meters): Participants walked 6 meters at a normal speed without running. The stopwatch started when the participant passed the starting point and stopped at the end of the distance (33).

2-minute walk test (2MWT): Performed on a 50-foot (15.24-meter) back-and-forth path. Participants were instructed to walk as fast as possible until they were told to stop (34).

Dynamic balance test: Participants walked on a straight 6-meter-long line marked on the floor with 5-cm-wide tape. Participants were asked to place one foot in front of the other and make sure that with each step, the heel of one foot was directly in front of the toes of the other foot (33).

Pain assessment: The Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) is an international and standardized questionnaire for assessing treatment outcomes in patients with KOA. This tool quantitatively assesses three criteria: pain (5 questions), joint stiffness (2 questions), and physical function (17 questions) (35).

Determination of Pressure During Blood Flow Restriction

To determine the required pressure for BFR, the subjects' systolic and diastolic blood pressure, and their thigh circumference were placed in the following formula, and the arterial occlusion point of each individual was obtained.

Arterial occlusion pressure = 5.893 (thigh circumference) + 0.734 (diastolic pressure) + 0.912 (systolic pressure) - 220.046 (36).

During the aquatic resistance exercise program, the BFR cuff was placed on the proximal part of the thigh and adjusted to 60% of the arterial occlusion pressure. Cuff pressure was maintained throughout the exercise (including rest periods) and released immediately after the final set of exercises. Cuff pressure was continuously monitored to maintain it at around 60% of resting arterial occlusion pressure (33). The BFR group performed exercises with a weight half the resistance training group weight.

Aquatic Resistance Exercise Program

The AQE program consisted of two training methods (resistance and resistance with BFR) for 8 weeks, with three weekly sessions (24 sessions). The exercises were performed in a temperature-controlled swimming pool (28–32 degrees Celsius) (37,38) with a depth of 1 to 1.5 meters (33,38). Both training groups performed their exercises in four sets, one set with 30 repetitions and three other sets with 15 repetitions, with a 1-minute rest between sets. However, one group performed these exercises simultaneously with BFR. The BFR cuff was closed after warm-up exercises outside the water with the pressure specified for each subject. It was opened after the end of the main exercises, and the subject performed the cool-down exercises without the cuff. The AQE + BFR group performed the exercises with the BFR cuff with the pressure specified for each subject with both legs. To help ensure safety and correct technique, the movement speed for all exercises was fixed at 2 seconds. All exercises were performed with perceived exertion between 9 and 11 on the Borg scale (6-20) and by attaching weights to the ankles (adjustable for each individual) in the water (33). In the first 2 weeks, the exercises were performed without weights, and every two weeks, the weight was increased by 1 kilogram until the weight reached 3 kilograms in the last two weeks. Exercises were performed first with the right leg and then with the left leg (10 minutes) (33) (Table 1).

Table 1. Resistance training program in water

Week	Warm-up	Lower body exercises	Sets × Repetitions	Weight (Kg)	Cool-down
1–2	Stretching and kinetic movements 10 min	Thigh flexion and extension	30 × 1	-	Stretching movements and walking 15 min
		Thigh abduction and extension	15 × 3		
		Walking forward and backward	24 m		
3–4	Stretching and kinetic movements 10 min	Knee flexion and extension	30 × 1	1	Stretching movements and walking 15 min
		Thigh flexion and extension Thigh abduction and extension	15 × 3		
		Walking forward and backward	24 m		
5–6	Stretching and kinetic movements 10 min	Knee flexion and extension	30 × 1	2	Stretching movements and walking 15 min
		Thigh flexion and extension Thigh abduction and extension	15 × 3		
		Walking forward and backward	24 m		
7–8	Stretching and kinetic movements 10 min	Knee flexion and extension	30 × 1	3	Stretching movements and walking 15 min
		Thigh flexion and extension Thigh abduction and extension Knee flexion and extension	15 × 3		
		Walking forward and backward	24 m		

Data Analysis Method

Descriptive statistics indicators of mean and standard deviation were used to describe the data. Also, in the inferential statistics section, the normality of the distribution and homogeneity of variance of the data was examined using the Kolmogorov-Smirnov and Levin tests, respectively. If the assumption of a parametric test was established, the one-way analysis of variance method was used (on the difference between the post-test and pre-test in each variable). Post hoc comparisons were conducted using Fisher's LSD test to identify specific group differences. The data were analyzed using SPSS software, and a significance level of $P \leq 0.05$ was considered.

Results

Table 2 presents the mean and standard deviation of the participant's demographic characteristics. To compare the effects of AQE and AQE + BFR based on the changes observed in the groups from pre-test to post-test, a one-way analysis of variance (ANOVA) was employed (Tables 3 and 4).

Based on the data reported in Tables 3 and 4, significant increases in heart rate variability components (HFpeak and LF/HFw), improvements in functional capacity tests (dynamic balance, chair stand test, and TUG test), and a significant reduction in the pain index were observed. However, no significant differences were found in other measured indices.

According to the LSD post hoc analysis, at the HF peak, the difference between the resistance training group ($P = 0.02$) and the control group was significant. In LF/HF walking, the difference between the resistance training group ($P = 0.001$) and the control group was significant. The difference between the resistance training group ($P = 0.001$) and the control group was significant in the pain index. The difference between the resistance training group ($P = 0.001$) and the blood flow restriction group ($P = 0.001$) was significant in the balance test. This means the blood flow restriction exercises improved the balance test more than the resistance exercises. The resistance training group ($P = 0.001$) and the blood flow restriction group ($P = 0.02$) significantly differed from the control group in the standing test. The difference between the resistance training group ($P = 0.02$) and the control group was significant in the TUG test.

Table 2. Demographic characteristics and values are shown as mean ± standard deviation

Variables	Age (years)	Menopausal age (years)	Weight (kg)	Body mass index (kg/m^2)
Group				
Resistance	56.69 ± 4.28	7.76 ± 4.14	71.05 ± 3.21	29.51 ± 5.18
BFR	53.21 ± 5.75	7.07 ± 3.07	70.56 ± 2.52	29.71 ± 3.78
Control	54.18 ± 5.75	7.36 ± 3.80	73.66 ± 7/74	30.59 ± 4.50

Discussion

In the AQE group, there was an improvement in HFpeak and LF/HFw, a reduction (improvement) in the chair stand test time, a reduction (improvement) in the TUG test time, and a decrease in pain.

The participants in the BFR group experienced significant improvement in balance and chair stand test performance. Improvements were also observed in other components of heart rate variability and functional capacity, but they were not statistically significant.

No studies were found to address the effects of AQE with and without BFR on heart rate variability. However, conflicting results have been reported regarding the effects of resistance exercises with BFR (39) and water-based aerobic exercises (40) on HRV. In the present study,

Table 3. Comparison of mean heart rate variability at rest and during walking in the three groups based on one-way analysis of variance

Test data		**Test descriptive**			**ANOVA**	
Variable	**Group**	**Pre-test**	**Post-test**	**Delta**	***f***	***p***
RMSSD	Resistance	98.70 ± 20.45	50.35 ± 52.51	29.80 ± 23.95	1.51	0.23
	BFR	36.05 ± 15.63	39.79 ± 21.51	14.45 ± 12.18		
	Control	43.13 ± 22.99	64.29 ± 48.58	27.74 ± 35.62		
SDNN	Resistance	51.57 ± 26.54	60.45 ± 58.22	17.09 ± 7.84	1.81	0.178
	BFR	45.11 ± 12.98	56.60 ± 36.90	11.75 ± 6.91		
	Control	123.33 ± 246.05	82.81 ± 67.09	23.36 ± 25.80		
LF peak	Resistance	0.062 ± 0.03	0.064 ± 0.020	0.016 ± 0.013	2.116	0.136
	BFR	0.058 ± 0.021	0.080 ± 0.033	0.034 ± 0.029		
	Control	0.081 ± 0.04	0.072 ± 0.025	0.025 ± 0.023		
HF peak	Resistance	0.28 ± 0.07	0.29 ± 0.06	0.078 ± 0.047	3.298	0.049*
	BFR	0.29 ± 0.087	0.26 ± 0.079	0.047 ± 0.039		
	Control	0.21 ± 0.10	0.26 ± 0.094	0.036 ± 0.040		
LF/HF ratio	Resistance	1.71 ± 1.30	1.63 ± 1.58	0.68 ± 0.43	0.96	0.393
	BFR	2.74 ± 2.76	1.69 ± 1.33	0.90 ± 0.95		
	Control	1.38 ± 1.35	1.24 ± 0.78	0.53 ± 0.48		
RMSSDw	Resistance	58.93 ± 44.15	35.09 ± 33.65	41.25 ± 39.15	0.548	0.58
	BFR	61.65 ± 52.78	47.96 ± 42.29	31.02 ± 31.19		
	Control	74.88 ± 35.34	49.40 ± 34.29	27.80 ± 28.33		
SDNNw	Resistance	70.04 ± 54.12	50.05 ± 34.54	40.98 ± 48.94	0.236	0.791
	BFR	75.34 ± 63.83	64.77 ± 40.24	48.31 ± 53.86		
	Control	94.02 ± 45.59	61.55 ± 32.52	35.43 ± 33.45		
LF peak	Resistance	0.073 ± 0.030	0.074 ± 0.027	0.029 ± 0.024	0.114	0.893
	BFR	0.091 ± 0.031	0.070 ± 0.024	0.037 ± 0.029		
	Control	0.094 ± 0.033	0.094 ± 0.036	0.039 ± 0.091		
HFpeakw	Resistance	0.26 ± 0.11	0.31 ± 0.12	0.13 ± 0.11	2.57	0.091
	BFR	0.31 ± 0.11	0.32 ± 0.11	0.079 ± 0.049		
	Control	0.23 ± 0.087	0.29 ± 0.10	0.064 ± 0.082		
LF/HFw ratio	Resistance	1.96 ± 1.66	13.78 ± 36.28	3.01 ± 2.69	4.74	0.015*
	BFR	8.32 ± 24.45	3.66 ± 4.90	1.75 ± 1.15		
	Control	2.37 ± 2.33	5.29 ± 9.80	0.76 ± 0.91		

(BFR = blood flow restriction; LFpeak = low-frequency; HFpeak = high-frequency; RMSSDw = RMSSDwalking; SDNNw = SDNNwalking; Hfpeakw = high-frequency walking; LFpeakw = low-frequency walking).
*Significance level is considered less than or equal to 0.05.

the increase in HFpeak and LF/HFw indicates increased parasympathetic activity and improved cardiovascular regulation, which can help reduce the risk of cardiovascular disease. The increased HF peak can be attributed to increased central blood volume during water immersion, triggering a baroreflex response that reduces SNA and increases PNA, thereby raising RMSSD and HF (40). The study by Tai et al (decrease in HF) highlighted the role of total exercise volume in regulating sympathovagal balance and upper body exercises and improving the physical health of participants (39). Hashimoto and Okamoto observed no changes in HRV indices. Although HF values increased at the beginning of the exercise, they remained unchanged throughout the session. These researchers attributed the difference in their findings to the fact that their participants were healthy young individuals and that they did not measure the hormones affecting vasodilation during or after water exercise, which may have influenced HRV (40). The improvement of LF/HF in water during aquatic exercise highlights the role of water in modulating the autonomic nervous system by reducing joint tension. The thermal and hydrostatic properties of immersion may enhance vagal tone and counteract the sympathetic dominance associated with knee osteoarthritis. The effect of blood flow restriction may be reduced or masked by the strong stimulus of water. Another finding of the present study was the improvement in the chair stand test in both water resistance training groups (with and

Table 4. Comparison of the mean of the functional capacity variable and the pain variable in the three groups based on one-way analysis of variance

Test Data		Test Descriptive			ANOVA	
Variable	**Group**	**Pre-test**	**Post-test**	**Delta**	***p***	***f***
Chair stand	Resistance	9.90 ± 1.93	7.97 ± 2.38	2.56 ± 1.39	0.002*	7.72
	BFR	10.18 ± 3.15	7.95 ± 1.55	1.90 ± 1.31		
	Control	10 ± 2.24	9.22 ± 2.18	0.70 ± 0.39		
TUG	Resistance	12.75 ± 7.21	7.69 ± 2.12	5.06 ± 6.24	0.05*	3.24
	BFR	10.44 ± 2.68	8.33 ± 1.70	2.61 ± 2.01		
	Control	10.61 ± 2.68	9.19 ± 2.29	1.1 ± 0.57		
Walking speed	Resistance	5.38 ± 2.69	3.56 ± 0.89	1.07 ± 0.52	0.07	2.74
	BFR	4.61 ± 0.98	3.53 ± 0.65	1.15 ± 0.73		
	Control	4.16 ± 0.76	4.40 ± 0.91	0.62 ± 0.43		
2-minute walk	Resistance	87.69 ± 26.66	103.07 ± 26.49	14.61 ± 9.67	0.17	1.81
	BFR	87.14 ± 16.83	97.5 ± 17.84	11.5 ± 8.50		
	Control	88.63 ± 19.50	95 ± 20.73	5.6 ± 8.18		
Dynamic balance	Resistance	7.69 ± 6.32	9.61 ± 6.13	1.38 ± 0.76	0.004*	6.65
	BFR	6.71 ± 6.00	8.92 ± 3.98	3.92 ± 17.3		
	Control	6.36 ± 4.94	6.72 ± 4.31	1.45 ± 93.0		
Pain	Resistance	49.92 ± 22.72	33.30 ± 21.10	20.61 ± 14.67	0.009*	5.46
	BFR	47.57 ± 10.39	37.71 ± 16.09	20 ± 12.78		
	Control	40.90 ± 16.54	40.54 ± 15.00	4.72 ± 3.97		

(BFR = blood flow restriction; TUG = timed up and go).
*Significance level is considered less than or equal to 0.05.

without BFR), which contrasts with the study by Araujo et al. (33) They attributed their results to the relative health of the participants at the beginning of their study. Resistance training with blood flow restriction has been shown to influence functional capacity tests and TUG test performance. Jørgensen and Marie reported improvements in the TUG test, which is consistent with our findings (26). However, Zwart et al who compared high-intensity resistance training with low-intensity resistance training, found no significant improvements in the TUG test; both types of exercises produced similar outcomes. This discrepancy may be due to differences in training protocols and the relative health of participants (41) and shows that low-intensity resistance training, even with blood flow restriction, can improve lower body function in people with knee osteoarthritis.

Moreover, no significant changes were observed in the functional capacity tests (2-minute walk test and walking speed) in the present study, aligning with the findings of Araújo et al (33). However, in the study by Rafique et al (2021), which investigated the effects of progressive resistance training on the functional capacity of individuals with KOA, improvements in walking speed were observed. This discrepancy might be attributed to the participants' dietary control and weight loss, which enhanced their functional capacity (42). The differences could be due to the heterogeneity of the participants, the baseline health status of the subjects, the severity of knee osteoarthritis, and age, which could have affected the results. On the other hand, older people do not exercise regularly, leading to mobility problems and loss of muscle mass. Their muscles become stiff and contract, putting more strain on their joints and bones during everyday activities, which can lead to inflammation or pain. The exercise may not be intense or long enough to make a significant difference. These results suggest that aquatic training did not have the intensity necessary to affect walking speed without additional interventions (such as weight loss). Another study result was the increase in balance in the water-based resistance training with the BFR group, which was consistent with Safdari but not with Araujo et al (33,43). Safdari et al reported improvements in static and dynamic balance due to resistance training in water, likely because water properties enhance sensory and proprioceptive receptors in the joints (43). Balance depends on the proper coordination of the visual, vestibular, and proprioceptive systems (43). The discrepancy with Araujo's study may stem from the fact that Araujo's research involved healthy postmenopausal women who likely had good baseline balance. In contrast, the current study included individuals with KOA, which can impair balance (33).

Based on the findings, functional capacity, and pain reduction significantly improved in the water-based resistance training group, consistent with the study by Askari Manesh and Rahnama (44) but inconsistent with Munukka et al (45). Askari Manesh and Rahnama conducted water resistance training on elderly women for eight weeks, three sessions per week. They reported pain reduction, which is related to the analgesic properties of water (44). Munukka et al however, reported no effects of water-based resistance training on short- and long-term pain reduction and physical performance. They attributed their results to the mild OA severity of the participants and the low baseline WOMAC index, which contrasts with the moderate OA severity of participants in the present study (45).

Based on the current research, eight weeks of water-based resistance training with or without BFR, performed three times per week, significantly influenced specific heart rate variability indices, functional capacity, and pain reduction indices. Moreover, the results indicated no significant differences between the effects of the two types of water resistance training on some HRV and functional capacity indices. However, further investigation over a longer duration and varying exercise intensities may provide more precise results.

Conclusion

According to the results of this study, a combination of resistance training in water and blood flow modulation can be used as a safe and effective intervention to improve the quality of life of patients with knee osteoarthritis. Also, the increase in LF/HFw and HF peak in the AQE group suggests that aquatic exercise activates the parasympathetic system. One limitation of this study was that some participants had pre-existing physical conditions, which may have influenced the study results.

The researchers could not monitor or regulate the participants' dietary habits, which might have affected the outcome. Since the study did not restrict or track the subjects' daily routines, variations in physical exertion and stress levels could have impacted the findings. Emotional stress, anxiety, and other psychological states are known to influence heart rate variability (HRV); however, they were not assessed in the present study.

Based on the results, we suggest that future studies should implement long-term monitoring using wearable devices to better understand the chronic adaptations of heart rate variability (HRV) in response to training interventions. The subjects' nutritional intake should be standardized or closely monitored during exercise programs to minimize confounding effects on HRV measurements. Additional research is needed to investigate the effects of different cuff pressures in BFR training to determine optimal protocols for cardiovascular and autonomic responses. Regular and systematic assessments of the control group should be conducted to ensure baseline comparability and detect any external influences on HRV. Participants' physical activities on non-intervention days should be precisely controlled or recorded to reduce variability in autonomic nervous system responses. Further studies should evaluate the role of key hormones (e.g., cortisol and catecholamines) in modulating HRV to clarify their contribution to autonomic regulation. A more detailed investigation of cardiac autonomic function in individuals with osteoarthritis (OA) is warranted, given the potential interactions between chronic pain, inflammation, and autonomic dysfunction.

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Conceptualization: Samaneh Baniasadi.
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Competing Interests
The authors declare that they do not have any conflict of interest.

Ethical Approval
The study was registered with the Ethics Committee of Birjand University with the code IR.BIRJAND.REC.1402.016

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