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Article

Numerical modelling of hydrodynamic thrust in patients using the HidroWalk for gait rehabilitation

Modelación numérica del empuje hidrodinámico en pacientes que emplean el HidroWalk para rehabilitación de la marcha

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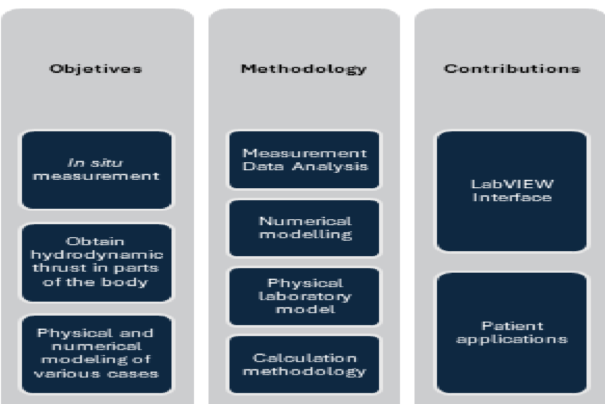
Abstract

This study employs a quantitative experimental methodology to investigate the relationship between flow rate, velocity, and depth with the hydrodynamic thrust exerted on a person using the HidroWalk for physical rehabilitation at CLUSI, Celaya-Salvatierra Campus. Hydrodynamic variables such as flow rate, velocity, depth, temperature, slope, and geometry are manipulated in a scaled variable-slope channel prototype located at the Applied Mechanics Laboratory in DICIVA, Irapuato-Salamanca Campus, which simulates the conditions of the HidroWalk. Computational tools and sensors were used for real-time measurements in both the HidroWalk and the prototype. Additionally, the FLOW3D software was used for the numerical analysis of the velocity and pressure fields generated in a person using the HidroWalk, and software such as ARDUINO and LabVIEW was utilized for developing the user interface installed in the HidroWalk. The study population includes gait alteration patterns simulated with two mannequins of 11 and 30 cm, providing a deep understanding of the relationship between hydrodynamic thrust and the force a user needs to exert for gait rehabilitation.



Hydrowalk, hydrodynamic-thrust, walk-rehabilitation

Resumen

El presente estudio emplea una metodología experimental cuantitativa para investigar la relación entre el caudal, la velocidad y la profundidad con el empuje hidrodinámico ejercido sobre una persona que utiliza el HidroWalk para rehabilitación física en la CLUSI del Campus Celaya-Salvatierra. Se manipulan variables hidrodinámicas como caudal, velocidad, profundidad, temperatura, pendiente y geometría en un prototipo de canal de pendiente variable a escala, ubicado en el Laboratorio de Mecánica Aplicada en la DICIVA Campus Irapuato-Salamanca, que simula las condiciones del HidroWalk. Se utilizaron herramientas computacionales y sensores para mediciones en tiempo real tanto en el HidroWalk como en el prototipo. Además, se empleó el software FLOW3D para el análisis numérico del campo de velocidades y presiones generadas en una persona que usa el HidroWalk, y software como ARDUINO y LabVIEW para el desarrollo de la interfaz de usuario instalada en el HidroWalk. La población de estudio incluye patrones de alteraciones de la marcha, simulados con dos maniquíes de 11 y 30 cm, lo que permitió una comprensión profunda de la relación entre el empuje hidrodinámico y la fuerza que necesita ejercer un usuario en la rehabilitación de la marcha.

Hidrowalk, empuje-hidrodinámico, rehabilitación-marcha

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Introduction

Currently, there are several types of neuromusculoskeletal injuries that affect gait in patients of all ages (Chan et al., 2012). These injuries require a physical rehabilitation process to re-educate gait and avoid permanent sequelae (Baskwill, 2007). Hydrotherapy is a prominent option due to the unique properties of water (Bartels et al., 2007; Bartels et al., 2016).

The use of a hydraulic channel such as the HydroWalk (see Fig. 1) provides a variable thrust according to the depth and speed of the water, which allows for gradual graduation and increase of resistance for patient rehabilitation.

Box 1

Figure 1
HidroWalk Channel (data sheet)

Hydrotherapy, or aquatic therapy, has been used throughout history for therapeutic and rehabilitative purposes. Hydrotherapy equipment such as tanks or pools are specially designed to carry out therapeutic activities in a controlled aquatic environment (Baskwill, 2007). Here is some general background to the use of hydrotherapy equipment:

Ancient History: Ancient cultures, such as the Romans and Greeks, used thermal baths and pools to promote health and well-being. Thermal baths were considered a common practice for the treatment and prevention of disease.

19th century: In the late 19th century, Austrian physician Sebastian Kneipp popularised hydrotherapy as part of his holistic approach to treatment, using hot and cold water baths as an integral part of his healing method (Bartels et al., 2007).

First Half of the 20th Century: During the First World War, hydrotherapy was used to rehabilitate wounded soldiers.

Immersion baths and other aquatic therapeutic methods were applied to improve mobility and reduce pain.

Development of Modern Hydrotherapy:

Throughout the 20th century, hydrotherapy evolved with the introduction of more advanced technologies and an understanding of the physiological benefits of water in the treatment of various conditions (Bartels et al., 2016; Silva et al., 2008).

Recent Decades: In recent decades, modern hydrotherapy equipment, equipped with jets, temperature control systems and specific accessories, have become common in physical rehabilitation settings, physiotherapy clinics and wellness centres.

Therapeutic applications: Hydrotherapy is used to treat a variety of conditions, such as muscle injuries, post-operative rehabilitation, arthritis and neuromuscular disorders.

Hydrotherapy in Sport: Athletes also turn to hydrotherapy for muscle recovery, reduction of inflammation and relief of joint stress (Bidonde et al., 2014; Häkkinen et al., 2008; Walter et al., 2014).

Hydrotherapy tanks are common in professional sports settings.

Scientific research: Interest in scientific research on hydrotherapy has grown, seeking to better understand the specific benefits and mechanisms behind aquatic therapy.

Hydrotherapy remains an evolving field, and hydrotherapy equipment continues to be a valuable tool in medical care and rehabilitation. Specific equipment such as the HydroWalk has features designed for specific purposes that require more detailed and up-to-date research.

Hydrotherapy remains an evolving field, and hydrotherapy equipment continues to be a valuable tool in medical care and rehabilitation. The specific application of equipment such as the Hydrowalk has particular features designed for specific purposes that require more detailed and up-to-date research.

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Currently, there are several types of neuromusculoskeletal injuries that result in gait impairment in patients of all ages (Chan et al., 2012).

These injuries require a physical rehabilitation process to re-educate gait and avoid permanent sequelae in individuals. Hydrotherapy is considered an excellent option due to the unique properties of water.

The use of a hydraulic channel such as the HidroWalk exerts a variable thrust according to the depth and speed of the water to which the patient is subjected, allowing the resistance to be graduated and increased gradually for rehabilitation.

It is essential to previously model the hydrodynamic behaviour in order to establish the depth and speed of the most suitable channel for each patient, according to their pathology and rehabilitation programme, seeking an optimal result that reduces discomfort during the process.

Materials and Methods

Hydrodynamic numerical model

Flow-3D is a computational fluid dynamics (CFD) software, which uses numerical techniques to solve the equations of motion of fluids, aiming to obtain three-dimensional transient solutions for 3 ultiphysics and multiscale flow problems. The equations in Flow-3D are formulated with area and volume functions.

These functions allow the representation of fractional volume/area obstacles called $FAVOR\ TM$ and are used to model complex geometric surfaces.

The general equation of mass continuity is:

$$V_F \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u A_x) + R\frac{\partial}{\partial y}(\rho v A_y) + \frac{\partial}{\partial z}(\rho w A_z) = R_{DIF} + R_{SOR} \quad [1]$$

The fluid velocity components at the three coordinates (u, v, w) are calculated from the equations of motion:

$$\frac{\partial u}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x} + vA_yR\frac{\partial u}{\partial y} + wA_z\frac{\partial u}{\partial z}\right\} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + G_x + f_x - b_x - \frac{R_{SOR}}{\rho V_F}(u - u_w - \delta u_s) \quad [2]$$

$$\frac{\partial v}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x} + vA_yR\frac{\partial v}{\partial y} + wA_z\frac{\partial v}{\partial z}\right\} = -\frac{1}{\rho}\left(R\frac{\partial p}{\partial y}\right) + G_y + f_y - b_y - \frac{R_{SOR}}{\rho V_F}(v - v_w - \delta v_s) \quad [3]$$

$$\frac{\partial w}{\partial t} + \frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x} + vA_yR\frac{\partial w}{\partial y} + wA_z\frac{\partial w}{\partial z}\right\} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + G_z + f_z - b_z - \frac{R_{SOR}}{\rho V_F}(w - w_w - \delta w_s) \quad [4]$$

The fluid-object interface, defined by the fluid volume method ($VOOF$), consists of three main components: the definition of the fluid function volume (Science, 2018) is set by:

$$\frac{\partial F}{\partial t} + \frac{1}{V_F}\left[\frac{\partial}{\partial x}(FA_x u) + R\frac{\partial}{\partial y}(FA_y v) + \frac{\partial}{\partial z}(FA_z w)\right] = F_{DIF} + F_{SOR} \quad [5]$$

Laboratory model

The laboratory flume used (fig. 2) has a variable slope and a constant rectangular section with a length of 2.32 m by 0.25 m wide and 0.18 m high. It has a 22-litre feed tank, a 2 hp pump and a 90-litre storage tank.

The walls of the channel are made of 0.012 m thick acrylic sheet, and the gate is made of the same material with a thickness of 0.006 m, 0.24 m wide and 0.15 m high, which was located in the middle of the length of the channel in order to avoid oscillations caused by the inlet and outlet spillways.

Box 2

Figure 2
Variable slope laboratory flume with acrylic electro-gate, DICIVA-UG

The Hidrowalk channel used (fig. 3) is made with a stainless steel structure, side panels and door with 10 mm tempered glass, temperature adjustable up to 35°C and dimensions 1.70 x 1.65 x 0.84 mts.

Box 3

Figure 3
Hydrotherapy equipment HidroWalk, DCSI-UG

Methodology to be developed

1. Purpose: A quantitative methodology with controlled experiments is proposed that allows the manipulation of certain hydrodynamic variables to obtain causal relationships such as hydrodynamic flow-thrust.

2. Research Design: Type of Study: Experimental with manipulation of independent variables.

Population and Sample: At least three cases of gait disturbance in need of rehabilitation using the Hidrowalk, with different anthropometric measurements (different sizes or ages).

3. Study Variables: Independent Variables: Flow or Flow Rate; average velocity; Depth or draft; water temperature; Slope of the channel and Hidrowalk, geometry and scale of the prototype.

Dependent Variables: The hydrodynamic force (thrust) provided by the fluid on an object.

4. Instruments and Materials: A FLOW3D numerical model is used to analyse the hydrodynamics of the model and the prototype, as well as LabVIEW software, ARDUINO and Mega 2560 boards, temperature sensors and digital velocity measurement equipment.

5. Procedures: Control Groups: A scenario without a patient is available for the purpose of measuring and obtaining hydrodynamic fields. A scenario with a non-running volunteer is available for measurement of hydrodynamic fields with an object.

6. Data analysis and processing: FLOW3D software will be used for visualisation and calculation only, and LabVIEW software will be used for measurement, instrumentation and operation of the Hidrowalk, providing the Flow-Thrust relationship for each patient.

Results

For the results section, as a first step, the results of the in situ measurement of the velocity components, depth before the fluid interacts with the patient and after it as shown in figure (4) are shown).

Box 4

Figure 4
In-situ velocity measurements at different depths

With the magnitudes of the velocities for different depths, the hydrodynamic forces or thrust generated in the patients were determined (table 1).).

Box 5
Table 1
Measurement results taken at the Hidrowalk

Speed	Prof A Top	Prof A Below	Download Esp.	Force	
(m/s)	(m)	(m)	(m^2/s)	(N)	(kgf)
1.31	1.05	0.91	1.59	86.702	8.843
1.29	0.91	0.83	1.27	45.532	4.644
1.18	0.78	0.72	0.92	31.234	3.185
1.07	0.55	0.51	0.59	14.072	1.435
0.83	0.37	0.32	0.31	11.438	1.166
0.79	0.20	0.16	0.15	3.494	0.356

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Once the values of the in situ measurement were obtained, the numerical simulation was carried out with the FLOW-3D software; the simulation conditions are 120 seconds and depth equals 1.60 m, the results of the variables of the pressure field (figure 5) and velocities generated by the circulation in the Hidrowalk are shown in figure (6).

Box 6

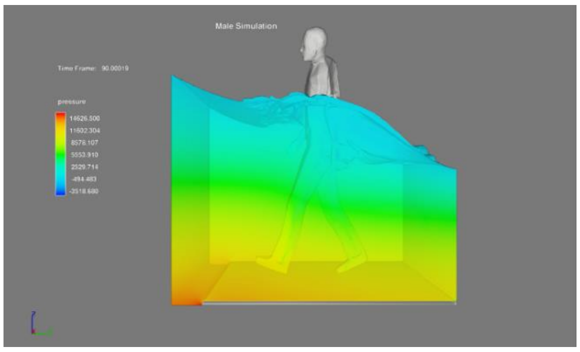


Figure 5

Numerical simulation of the pressure exerted by the flow over the patient using Hidrowalk

Box 7

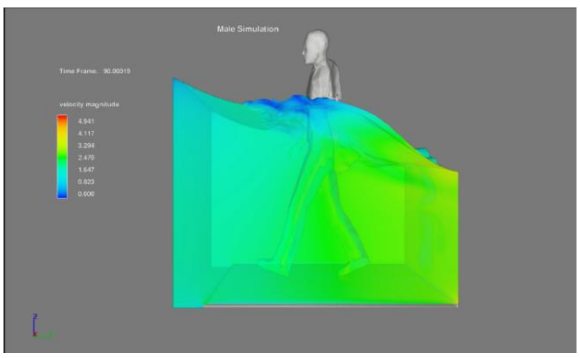


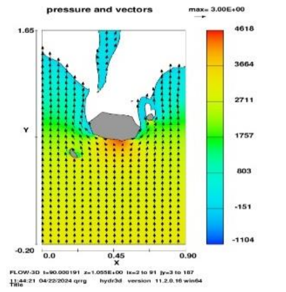
Figure 6

Numerical simulation of flow velocity over the patient using Hidrowalk

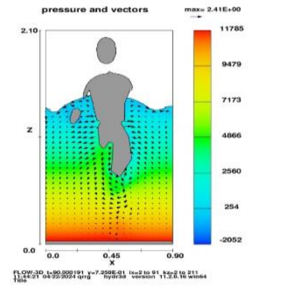
The simulations provide information on the thrust generated in the calves, thighs, abdomen and forearms under different hydrodynamic conditions and monitor the velocities and depths in the Hidrowalk with the sensors in real time.

Figures (7a, 7b and 7c) show the pressure exerted by the fluid on the patient in more detail, where it should be noted that the areas with greater thrust are the thighs because they have a larger contact area, likewise, the abdomen region shows the interaction of water with air (free surface) and therefore lower pressure and velocity.

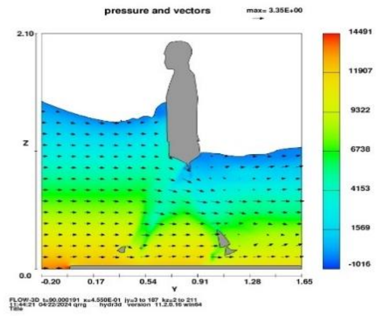
Box 8



a) see XY



b) see XZ



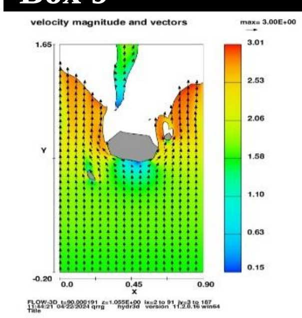
c) see YZ

Figure 7

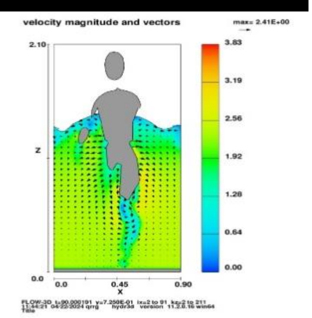
Pressure field results: a) top view XY; b) front view XZ and c) side view YZ

Similarly, figure (8) shows the results of the velocity field for the different views, likewise, it can be observed that the velocities with the greatest magnitude are in the thighs and which present a greater work in rehabilitation.

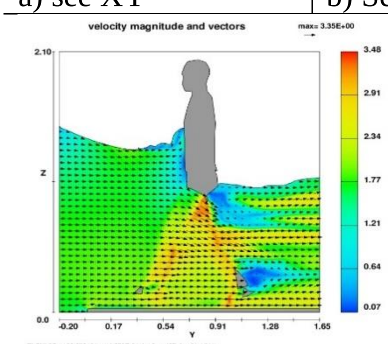
Box 9



a) see XY



b) See XZ



c) See YZ

Figure 8

Velocity field results: a) top view XY; b) front view XZ and c) side view YZ

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Once the simulation was completed, the scaled simulation was carried out in the variable slope channel for two cases, the first with an 11 cm dummy (figure 9a) and the second with a 30 cm dummy (figure 9b). The use of two dummies for the experimental simulation was due to having two patients with different heights (child and adult), where they are subjected to the same flow rate provided by the modified Hidrowalk at a scale of 1:11 respecting the hydraulic similarity conditions.

Box 10

a) 11 cm mannequin b) 30 cm mannequin

Figure 9
Manikin for laboratory channel simulation:a) de 11 cm y b) de 30 cm

Figure (10a) shows the scale model for the 11 cm dummy, which was placed in the variable slope channel (figure 10b).

Box 11

a) variable slope channel model b) 11cm mannequin

Figure 10
Operation of the variable slope channel for the 11 cm manikin

Similarly, figure (11) shows the operation of the channel for the 30 cm dummy.

Box 12

a) variable slope channel model b) 11cm mannequin

Figure 11
Operation of the variable slope chute for the 30 cm dummy

The speed was measured with a Vernier current meter (figure 12) for each dummy, where the records obtained are shown in figure (13) for the 11 cm dummy and in figure (14) for the 30 cm dummy.

Box 13

Figure 12
Vernier flow meter (Flow-meter)

Box 14

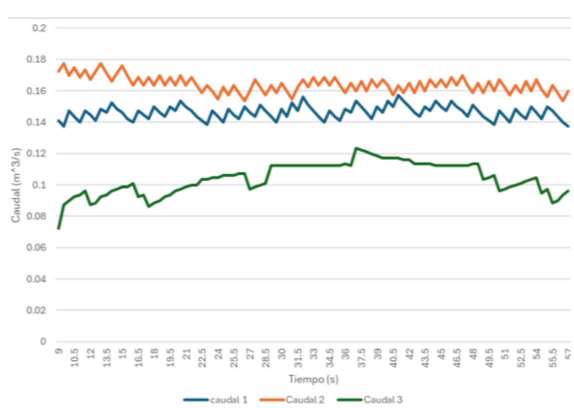

Figure 13
Measurement of the average flow rate for the 11 cm dummy

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Box 15

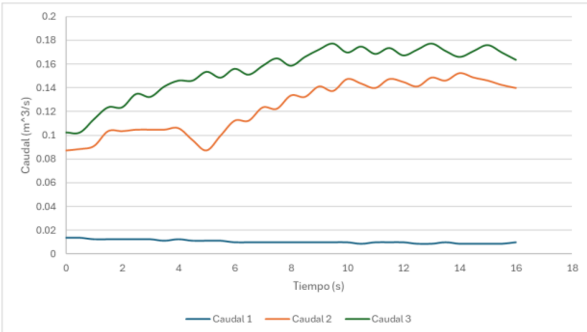

Figure 14
Measurement of the average flow rate for the 30 cm dummy

The measurement results are shown in table (2) for the different dummy sizes.

Box 16

Table 2
Measurement results taken in the variable slope channel for the 11 cm and 30 cm dummies.

Maniquí	Caudal (m^3/s)	Force (kgf)
11 cm	0.155	3.867
30 cm	0.168	4.025

Subsequently, the programme was developed in Arduino (figure 15) and the user interface in LabVIEW (figure 16), which will allow adjustments to be made both in flow velocity and depth measurement to calculate the hydrodynamic thrust generated in patients with the calibration of the hydrodynamic variables and the velocity field obtained from the FLOW3D for different cases.

Box 17

```
void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);


//FIN VOID SETUP
}

void loop() {
  // put your main code here, to run repeatedly:
//PRIMER SENSOR

//INSTRUCCIONES SENSOR 1
pinMode(trigs1,OUTPUT);
pinMode(echos1,INPUT);
digitalWrite(trigs1,LOW);
digitalWrite(trigs1,HIGH);
delayMicroseconds(10);
digitalWrite(trigs1,LOW);

t=pulseIn(echos1,HIGH);
ds1=long(0.01715*t);
```

Figure 15
Arduino code section for depth sensor control and value calculation

The purpose of this code is to calculate the flow rate, interpolated velocities, drag coefficients, and hydrodynamic force or thrust at different depths where the required body parts are located.

This code was incorporated into a user interface executable in LabVIEW (figure 16), where it was installed on a computer connected to the Hidrowalk and which allows the Hidrowalk to be operated and its sensors to monitor its operation.

Box 18

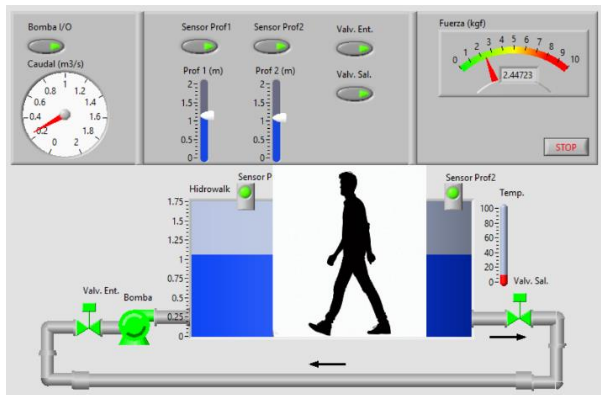

Figure 16
Hidrowalk Control Interface in LabVIEW

This interface allows to calculate the speed through the opening of valves either manually or motorised, with it the necessary hydrodynamic thrust is obtained for each patient according to their condition and to help them in their gait rehabilitation process before the subject enters the Hidrowalk.

Conclusions

In this study, a comprehensive investigation combining in situ measurements, numerical simulations and scale experiments was conducted to evaluate the hydrodynamic thrust generated in patients during rehabilitation in an aquatic environment. The results obtained revealed important findings:

1. The in situ measurements provided accurate data on flow velocities and depths before and after the interaction with the patient, as well as the determination of hydrodynamic forces on different parts of the body.

2. Numerical simulations with FLOW-3D software allowed visualisation and quantification of the pressure field and velocities generated by the circulation in the aquatic environment, providing valuable information on the thrust distribution in specific areas such as calves, thighs, abdomen and forearms.

3. Scaled experiments in a variable slope channel with dummies of different sizes provided comparative data on flow velocity and hydrodynamic buoyancy under conditions similar to those of the Hidrowalk, validating the results obtained in the simulations.

4. The development of an Arduino program and user interface in LabVIEW enabled the calibration and control of the Hidrowalk, facilitating the adaptation of flow velocity and depth measurement to calculate the hydrodynamic thrust required for each patient's rehabilitation.

Taken together, these findings highlight the importance of understanding and quantifying hydrodynamic buoyancy in aquatic environments to improve rehabilitation processes and design of devices such as the Hidrowalk, thus contributing to the advancement of quality of life and well-being of rehabilitation patients.

Conflict of interest

The authors declare that they have no conflicts of interest. They have no known competing financial interests or personal relationships that might have appeared to influence the article reported in this paper.

Authors' contribution

Gamiño-Ramírez, Edith Alejandra: Contributed to the project with the idea, or need, and the Hidrowalk team.

Herrera-Díaz, Israel Enrique: Contributed with the in situ measurement, programming in Arduino and the development of the interface and calculation memory in LabVIEW.

Ugalde-Zanella, Valeria: Contributed with the methodology of using the results with the subjects and interpretation of results.

Torres-Bejarano, Franklin Manuel: Contributed with the numerical modelling in Flow3D for the comparison of results and validation of the calculation memory.

Availability of data and materials

Data obtained in this research are available upon request from the authors.

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Abbreviations

Ax: Is the fractional area open to flow in the x direction
(Ay, Az): Are similar area fractions for the flow in the y- and z-directions, respectively
(bx, by, bz): Are flow losses in porous media or through porous baffle plates
cF: Is the constant whose reciprocal is sometimes referred to as the turbulent Schmidt number
(fx, fy, fz): Are viscous accelerations
(Gx,Gy,Gz): Are bodily accelerations
Rdif: Is the turbulent diffusion term
Rsor: Is the mass source term
VF: Is the fractional volume open to flow
(u, v, w): Are the velocity components are in the co-ordinate directions of (x, y, z) o (r, θ, z).
ρ: Is the density of the fluid
υF: Is the diffusion coefficient

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