Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review

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***Abstract*— Benchmarks have long been used to verify and compare the readiness level of different technologies in many application domains. In the field of wearable robots, the lack of a recognized benchmarking methodology is one important impediment that may hamper the efficient translation of research prototypes into actual products. At the same time, an exponentially growing number of research studies are addressing the problem of quantifying the performance of robotic exoskeletons, resulting in a rich and highly heterogeneous picture of methods, variables and protocols. This review aims to organize this information, and identify the most promising performance indicators that can be converted into practical benchmarks. We focus our analysis on lower limb functions, including a wide spectrum of motor skills and performance indicators. We found that, in general, the evaluation of lower limb exoskeletons is still largely focused on straight walking, with poor coverage of most of the basic motor skills that make up the activities of daily life. Our analysis also reveals a clear bias towards generic kinematics and kinetic indicators, in spite of the metrics of human-robot interaction. Based on these results, we identify and discuss a number of promising research directions that may help the community to attain a comprehensive benchmarking methodology for robot-assisted locomotion more efficiently.**

***Index Terms*— Benchmarking, locomotion, walking, posture, assessment, wearable robots, orthoses.**

I. INTRODUCTION

WEARABLE robots are experiencing an unprecedented era. Many research prototypes have been successfully turned into commercial products and are now facing a rapidly evolving market, characterized by diverse applications and needs. While the potential of wearable robotics technology is indisputable, demonstrating its value on a quantitative basis is challenging. Previous reviews have highlighted weaknesses and difficulties in providing reliable evidence of the clinical usefulness of these devices, possibly due to a lack of clear and rigorous evaluation methods [1], [2]. At the same time, the robotics community has demonstrated an increasing interest in benchmarking as a way to scientifically assess and compare the performance of exoskeletons [3]. However, no agreed methodology, best practices or standards have been made formally available so far [4]. Currently, the principal approach to compare exoskeletons has been through competitions, such as Cybathlon [5]. The major drawback of competitions is that scores are usually based on very simple metrics, for example accomplishment of a task and/or time to completion, which can hardly be used to characterize the multiple aspects of exoskeleton performance. Fortunately, the scientific literature has produced hundreds of studies that focused, directly or indirectly, on the evaluation of exoskeletons, which has resulted in a multitude of available methods and variables. However, the great variability in procedures, experimental settings and metrics, makes these methods difficult to apply to other devices and environments, which impedes an objective comparison across systems. A unified and broadly applicable benchmarking methodology for performance evaluation of wearable robotic systems is therefore eagerly anticipated. In line with this objective, this review aims to identify and bring together the most promising methods, metrics and experimental procedures available in the literature to assess robotic-assisted motor skills. We focused on lower limb exoskeletons for gait assistance and rehabilitation, following on our previous efforts in the field of benchmarking bipedal locomotion [6]. We screened more than nine hundred papers which, after a careful selection process, resulted in a total of 187 relevant publications. We structured our analysis to address two main research questions:

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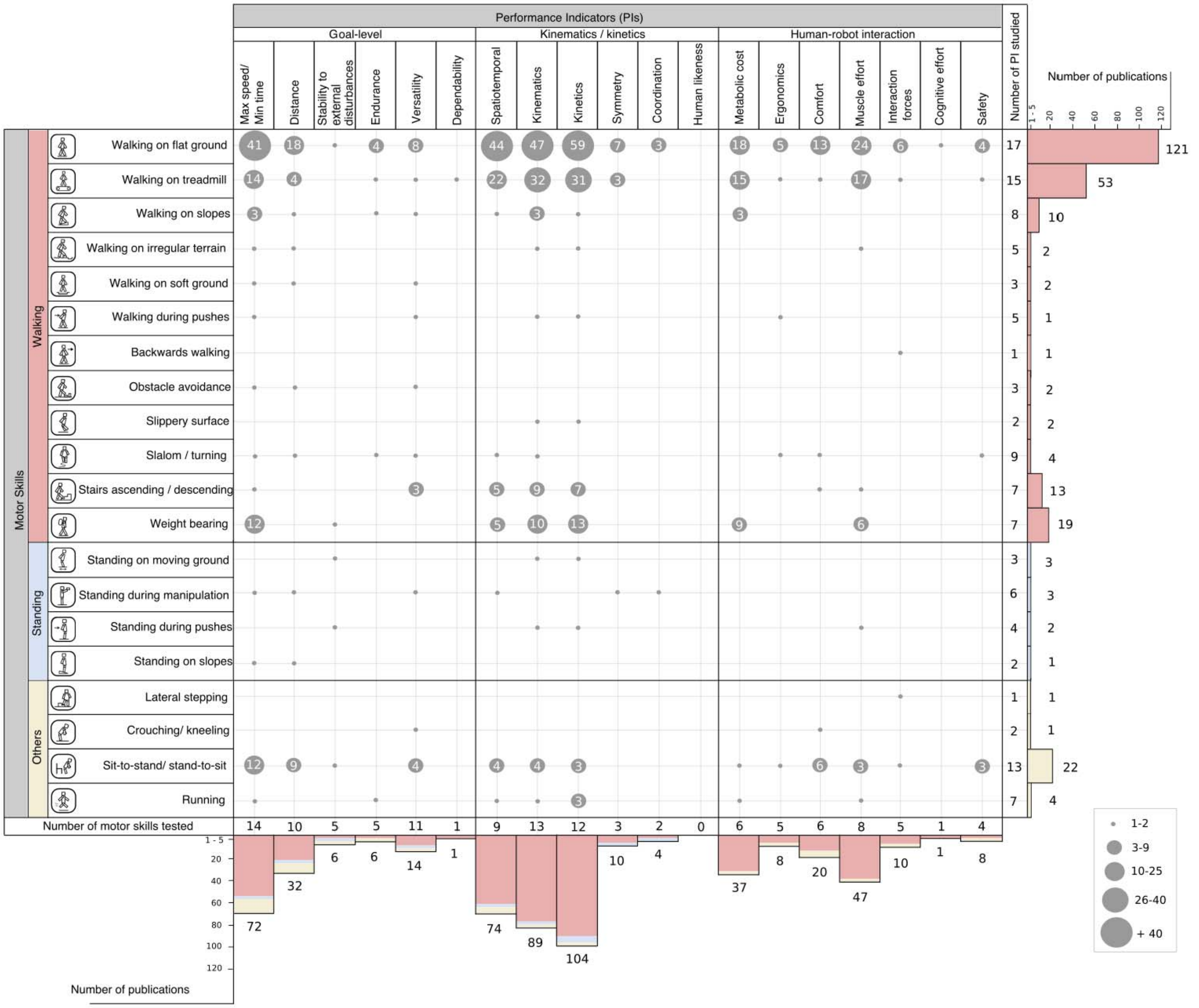


Fig. 1. Taxonomic overview of the reviewed works. The size of each circle (and the number inside it) indicates the number of reviewed works covering a given motor skill (row) and PI (column). Bars on the right indicate the total number of publications covering the corresponding motor skill. Bars on the bottom indicate the number of publications that proposed or used the corresponding PI. The colours of the bars represent the three main categories of motor skills (walking, standing, others). The numbers in the last column indicate the number of PIs covered by each motor skill, and vice versa for the numbers in the last row.

- Which motor skills are considered when evaluating the functionality of a lower limb exoskeleton?
- Which variables and metrics are used to characterize performance?

Section II presents the literature search methodology, which includes the search query, the exclusion criteria, and the taxonomy used to classify results by motor skills and performance indicators. Section III reports the results of our analysis and identifies the most relevant trends. In Section IV we present a critical analysis of the results, addressing the research questions posed and identifying the main drawbacks and the most promising future directions. A conclusion is provided in Section V.

II. METHODS

We obtained 923 titles from an initial search of the Scopus database using the following query string on paper title, keywords and abstract, on papers published between January 1989 and April 2018:

(locomot OR gait* OR walk* OR “body transport*”) AND (test* OR assess* OR measure* OR benchmark* OR evaluat* OR quantif*) AND (“wearable robot*” OR exoskelet* OR “powered ortho*”)*

After reading titles and abstracts, we excluded duplicated publications and those that met one or more of the following criteria: not related to wearable robots; not focused on testing locomotion performance; not including physical prototypes; restricted to testing perception abilities of the system; focused on brain computer interfaces (BCI); focused on clinical assessment. We added a further ten publications resulting from a further search of those scenarios that produced scarce results in the previous search, for example standing, balance, soft ground, irregular terrains, or slippery surfaces. After reading the full texts, we discarded a further 24 articles, resulting

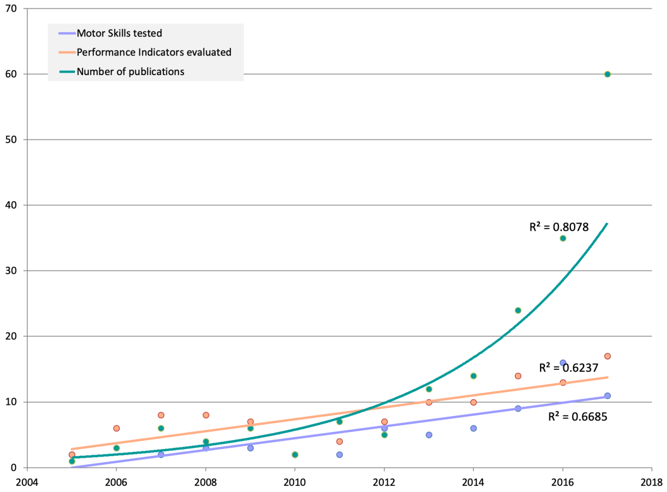


Fig. 2. Number of publications, motor tasks and PIs over time.

in a total of 187 papers. We classified the papers using a twofold taxonomy composed of motor skills and performance indicators (PIs), as shown in Figure 1. Motor skills have been grouped into the following three categories:

- Walking skills, which included walking on flat ground, treadmill, slopes, irregular terrains, soft ground, slippery surfaces, when pushed, backwards walking, overcoming obstacles, slalom or turning, ascending or descending stairs, and walking while bearing additional weight.
- Standing skills, which included standing on moving surfaces, on slopes, in the presence of pushes, and during manipulation.
- Other skills, which included lateral stepping, crouching or kneeling, sit-to-stand or stand-to-sit, and running.

PIs were clustered into:

- Goal-level variables, which included maximum speed or minimum time, distance achievable by the robot, stability, endurance, versatility and dependability.
- Kinematics/kinetics variables, which included spatiotemporal parameters, joint or limb kinematics and kinetics, symmetry, coordination and human likeness.
- Human-robot interaction variables, which included metabolic cost, ergonomics, comfort, muscle effort, interaction forces, cognitive effort and safety.

III. RESULTS

As shown in Figure 2, the number of publications has increased exponentially over the years. The number of motor skills and PIs considered also showed an increase, but with a linear trend. The distribution of the reviewed works across the different categories is presented in Figure 1.

A. Motor Skills

1) Flat Ground Walking: This is the most frequent motor skill in the literature, with 121 publications [7]–[127]. Overall, these publications cover most of the PIs included in our taxonomy (see last column of Figure 1), of which the more relevant are kinetics, kinematics, spatiotemporal parameters and maximum speed and/or minimum time.

2) Walking on a Treadmill: This is the second most popular motor skill in the literature, with 53 publications [10], [11], [13], [24], [58], [86], [103], [105], [109], [128]–[170] and 15 different PIs covered, kinematics, kinetics and spatiotemporal parameters being the most used.

3) Walking on Slopes: We found ten publications [58], [67], [75], [76], [79], [80], [94], [117], [171], [172] covering this motor skill, spanning eight different PIs, of which max. speed/ min. time, kinematics and metabolic cost had the highest prevalence.

4) Walking on Irregular Terrains: Only two publications, [76], [173], covered this motor skill. Kinematics, kinetics, max. speed/ min. time, distance and metabolic cost were the PIs considered.

5) Walking on Soft Ground: We found only two publications, [75], [80], which considered this scenario. The evaluation of this motor skill was based on goal-level PIs, including max. speed/ min. time, distance and versatility.

6) Walking During Pushes: Only one publication [50] was found on this motor skill. Five PIs were assessed for this evaluation: max. speed/ min. time, versatility, kinematics, kinetics and ergonomics.

7) Backwards Walking: Only one paper [127] was found on this skill, focusing on the assessment of human-robot interaction forces.

8) Obstacle Avoidance: We found only two papers, [75], [80], that considered this scenario, with three goal-level PIs proposed: max. speed/ min. time, distance and versatility.

9) Slippery Surface: Only two papers, [174], [175], focused on this motor skill. Three PIs were proposed for its evaluation; these were range of motion, angles and torques.

10) Slalom and/or Turning: Four papers, [45], [75], [80], [117], evaluated locomotion involving turns, with a very heterogeneous set of PIs (see Figure 1 for details).

11) Ascending and/or Descending Stairs: With 13 publications, [20], [31], [32], [58], [67], [79], [97], [101], [117], [147], [176]–[178], this is the fifth most considered motor skill in this review. Seven PIs were proposed for its evaluation, the most frequent being kinematics, kinetics, spatiotemporal variables and versatility.

12) Weight Bearing: Weight bearing is the fourth most covered motor skill, with 19 publications, [9], [20], [34], [51], [53], [73], [128], [130], [146], [149], [153], [160], [164], [172], [179]–[184]. The most frequent PIs were kinetics, kinematics, maximum speed, spatiotemporal parameters, muscle effort and metabolic cost.

13) Standing on Moving Ground: We found three papers [175], [185], [186] covering this motor skill. The five PIs proposed belonged mainly to the kinematics/kinetics category.

14) Standing During Manipulation: Three papers, [59], [75], [187], covered this motor skill, with six different PIs, the most relevant being max. speed/ min. time, and spatiotemporal PIs.

15) Standing During Pushes: Only two papers, [186], [188], covered this motor skill, with four different PIs: kinematics, kinetics, stability to external disturbances and muscle activation.

16) Standing on Slopes: We only found one paper [75] that studied exoskeleton performance while standing on a slope. Two different goal-level PIs were presented: max. speed/min. time and distance.

17) Lateral Stepping: We only found one paper [127] assessing this skill, which focused primarily on interaction forces.

18) Crouching and/or Kneeling: Only one paper [73] assessed this skill, with two different PIs: versatility and comfort.

19) Sit-to-Stand/Stand-to-Sit: Chair sitting and standing is the third most covered motor skill in this review, with 22 publications, [8], [21]–[23], [32], [35], [42], [44], [51], [58], [59], [73], [75], [80], [84], [96], [98], [99], [117], [123], [189], [190]. This skill was evaluated with a high variety of PIs (13), the most frequent being max. speed/ min. time, distance, comfort, versatility, spatiotemporal parameters and kinematics.

20) Running: We found four publications [104], [191]–[193] that assessed running while wearing an exoskeleton. Seven PIs were presented for this evaluation and the most relevant was kinetics.

B. Performance Indicators

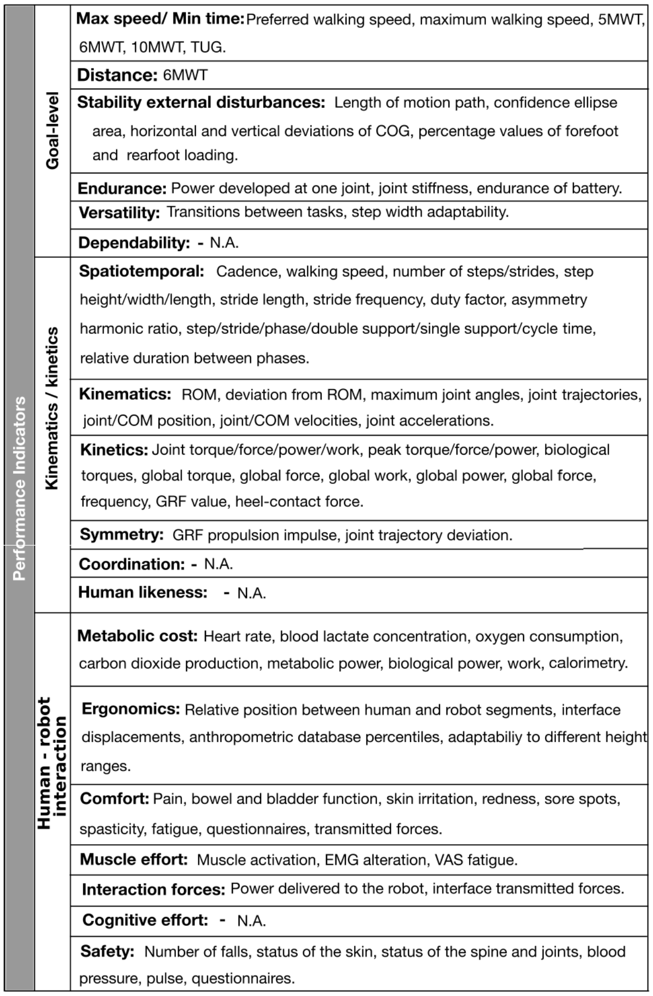
1) Maximum Speed/Minimum Time: This category refers to the minimum time the robot needed, or the maximum speed it achieved, to correctly perform a certain motor skill. It is one of the preferred metrics for performance evaluation in this review, with 72 appearances in papers, spanning 14 different motor skills. The most common specific PIs used in this category (see Figure 3) are patient's preferred speed, maximum walking speed and execution time, most of them calculated during clinical tests, such as the 10 Meter Walking Test (10MWT), the 6 Minute Walking Test (6MWT) and the Timed Up and Go (TUG) test.

2) Distance: The distance covered by the exoskeleton is frequently used when evaluating exoskeleton performance, with 32 occurrences in papers that covered ten different motor skills. We found that the 6MWT is the preferred PI in this category.

3) Stability to External Disturbances: This category includes indicators such as deviations of the centre of gravity (COG), forefoot and rearfoot loading, length of motion path or confidence ellipse area. Stability was evaluated in six papers that considered the following scenarios: flat walking, weight bearing, standing on moving ground and during pushes, and sit-to-stand.

4) Endurance: This evaluation is generally requested to test the robot's ability to perform long periods of functioning or multiple cycles of work. We found seven publications evaluating these aspects, which covered eight motor skills. The most frequent PIs considered here were power development per joint, joint stiffness and battery usage.

5) Versatility: Versatility is used to describe the exoskeleton's ability to cope with different motor skills in the same run. This aspect were considered in 14 publications that spanned 12 motor skills. The specific PIs used were step width adaptability and number of successful transitions between tasks.



Performance Indicators	Goal-level	**Max speed/ Min time:** Preferred walking speed, maximum walking speed, 5MWT, 6MWT, 10MWT, TUG.
		Distance: 6MWT
		Stability external disturbances: Length of motion path, confidence ellipse area, horizontal and vertical deviations of COG, percentage values of forefoot and rearfoot loading.
		Endurance: Power developed at one joint, joint stiffness, endurance of battery.
		Versatility: Transitions between tasks, step width adaptability.
		Dependability: - N.A.
	Kinematics / kinetics	**Spatiotemporal:** Cadence, walking speed, number of steps/strides, step height/width/length, stride length, stride frequency, duty factor, asymmetry harmonic ratio, step/stride/phase/double support/single support/cycle time, relative duration between phases.
		Kinematics: ROM, deviation from ROM, maximum joint angles, joint trajectories, joint/COM position, joint/COM velocities, joint accelerations.
		Kinetics: Joint torque/force/power/work, peak torque/force/power, biological torques, global torque, global force, global work, global power, global force, frequency, GRF value, heel-contact force.
		Symmetry: GRF propulsion impulse, joint trajectory deviation.
		Coordination: - N.A.
		Human likeness: - N.A.
	Human - robot interaction	**Metabolic cost:** Heart rate, blood lactate concentration, oxygen consumption, carbon dioxide production, metabolic power, biological power, work, calorimetry.
		Ergonomics: Relative position between human and robot segments, interface displacements, anthropometric database percentiles, adaptabiliy to different height ranges.
		Comfort: Pain, bowel and bladder function, skin irritation, redness, sore spots, spasticity, fatigue, questionnaires, transmitted forces.
		Muscle effort: Muscle activation, EMG alteration, VAS fatigue.
		Interaction forces: Power delivered to the robot, interface transmitted forces.
		Cognitive effort: - N.A.
		Safety: Number of falls, status of the skin, status of the spine and joints, blood pressure, pulse, questionnaires.

Fig. 3. Overview of the performance indicators found on the reviewed works engaged in the three main categories. The number of works covering each PI is presented in brackets. CoG: Center of Gravity CoM: Center of Mass; 5MWT: Five Meter Walking Test; 6MWT: Six Minute Walking Test; 10MWT: Ten Meter Walking Test; TUG: Timed Up and Go.

6) Dependability: Dependability, defined here as the robot's ability to operate without failures or decreased performance was mentioned in only one paper, focused on treadmill walking. We could not find any specific PI to measure this ability.

7) Spatiotemporal Parameters: This category is the fifth most considered in literature, used in almost all walking skills, except for walking on uneven terrains and during pushes. We found 19 different PIs, the most frequent being cadence, walking speed, number of steps, step length, stride length and phase time.

8) Kinematics: Kinematic variables are used in almost half of the publications reviewed. These cover almost all motor skills, except for soft and slippery grounds, obstacle avoidance, standing during manipulation and crouching/kneeling. Among the PIs found, the most popular were joint angular trajectories, range of motion (ROM), speed and COM position.

9) Kinetics: The same considerations given for kinematics apply here. Fifteen different PIs have been proposed in this category. The most frequent were global torques, global forces, global power and ground reaction forces (GRF).

10) Symmetry: Symmetry has been evaluated in ten publications, most of them focusing on flat walking, and to a minor extent on standing. The main relevant PIs were GRF propulsion impulse and joint trajectory deviation.

11) Coordination: We found five publications on this aspect, four of them on flat walking and one on standing during manipulation. No specific PIs were proposed.

12) Human Likeness: No paper explicitly mentioned this aspect.

13) Metabolic Cost: This kind of measurement was found in 37 publications, most of them focusing on flat or treadmill walking, and to a minor extent on weight bearing or slope walking. Heart rate, blood lactate concentration, oxygen consumption, carbon dioxide production, metabolic power, biological power, work and calorimetry are the most frequent PIs.

14) Ergonomics: Ergonomics was considered in eight publications, most of them covering flat or treadmill walking, with sporadic applications to other motor skills (see Figure 1 for details). The main PIs used were human-robot relative position, interface displacements, anthropometric database percentiles, and adaptability to different height ranges.

15) Comfort: Comfort, defined here as the user's perception of the human-robot interaction, was covered by 20 publications, and mostly applied on flat ground walking and sit-to-stand/stand-to-sit skills. Among the ten PIs found, the most relevant were pain scales, clinical questionnaires, and user sense of comfort.

16) Muscle Effort: This is the most common aspect employed for the assessment of human-robot interaction. It was covered by 47 publications, half of them applied to flat walking, followed by treadmill walking, weight bearing, sit-to-stand and standing during pushes. Muscle effort is generally assessed by measuring electromyographic (EMG) activity, which is generally processed for posterior onset detection and muscle activity recognition. Also muscle alteration rates and the visual analogue scale of fatigue (VAS-F) have been found as indicators of muscle effort.

17) Interaction Forces: We found ten publications covering this aspect. Seven of them covered flat ground walking, another two covered treadmill walking and sit-to-stand/stand-to-sit, and another one covered backwards and lateral stepping. Power delivered to the robot, interface transmitted forces and interaction forces were the only three PIs found in this category.

18) Cognitive Effort: We found only one publication mentioning cognitive effort as a performance metric. It was applied to flat walking but no specific metric was found.

19) Safety: The evaluation of safety was proposed by eight publications. Seven different PIs were identified: number of falls, skin, spine and joint status after using the robot, blood pressure, heart rate and clinical questionnaires.

IV. DISCUSSION

We observed an increasing relevance of performance evaluation in the field of lower limb exoskeletons. This trend, visible in the exponential growth in the numbers of papers (see Figure 2) is, however, only in part accompanied by an increase in the range of motor skills and PIs that are studied, which show a more moderate increment. This, together with our taxonomic analysis summarized in Figure 1, demonstrates that the current evaluation methods for exoskeletons are still restricted to a small portion of the applicable motor skills and PIs. In the following sub-sections, we will consider in more detail the possible causes of this situation and point towards relevant future research directions.

A. Motor Skills

The number of papers focusing on flat ground and treadmill walking prevail by one order of magnitude over any other motor skill considered in our taxonomy. This fact is not surprising considering that straight walking is the primary functional requirement for lower limb exoskeletons, and that gait analysis has a long scientific history. However, in our opinion, the dominance of flat walking does not imply that the other motor skills are less relevant. The activities of daily living are composed of a rich repertoire of functions, which should be taken into account to demonstrate the feasibility of exoskeletons to operate in real environments. For instance, irregular terrains such as grass, stones, sand, carpets, gravel and holes, have been largely overlooked in the literature. The same has happened to many other motor skills, such as lateral stepping, crouching/kneeling, turning or standing. All these motor skills showed a prevalence lower than five publications each (less than 2% of the total). In particular, we found the shortage of tests on balance skills particularly alarming, since balance is a crucial aspect of bipedal locomotion [194]. This may be explained by the fact that most exoskeletons still do not have active balance control. However, assuming that this ability will be implemented in future prototypes, we strongly believe that rigorous methodologies to evaluate standing and balance skills will be particularly beneficial.

A group of four motor skills received particular attention, after flat and treadmill walking. These are walking on slopes, stair ascending and descending, weight bearing and sit-to-stand/stand-to-sit. The interest in these motor skills can be explained by their prevalence in many application scenarios (e.g. clinical, domestic, industrial), which makes them essential for both rehabilitation and assistance purposes. Nevertheless, the proposed scenarios still fail to consider the entire spectrum of conditions, for example slope inclination, step height and chair typology. We believe that, in general, for the entire set of motor skills represented in Figure 1, the scientific community will significantly benefit from comprehensive testbeds that reproduce and synthesize the variability of real ecological conditions. These testbeds should preferably be sensorized to allow direct measurement of the relevant variables, and be fully replicable, to allow direct comparison between labs and robotic solutions.

B. Performance Indicators

In the *goal-level* category, global time and distance are two very popular indicators. They are generally used as global descriptors of system performance, and are particularly useful during competition approaches for their simplicity and immediacy of use. In spite of these practical advantages, we consider them insufficient to validate or quantify the performance of an exoskeleton system. A PI that has been particularly disregarded in the literature is the stability against external disturbances. We consider that this aspect is very relevant, since external disturbances are often present in real life scenarios. We strongly encourage its evaluation and characterization in the future. Versatility and dependability are a further two aspects that have not yet been sufficiently addressed by the community. This may be explained by the fact that they are highly related to high readiness levels, still not achieved by most current prototypes. Another interpretation is that these concepts are still not formally defined in the field of wearable robots. This draws attention to the important problem of terminology, which should be addressed by the community in order to find common understanding on these aspects.

The *kinematics/kinetics* category is extremely popular in the assessment of exoskeletons. This is probably due to the fact that these variables can be extracted from the sensors of the robot or estimated by standard motion capture systems. These PIs have the potential to grasp the entire complexity of limb dynamics but, on the other hand, the obtained results are often difficult to contrast and replicate due to the lack of common standard setups, data labelling or experimental protocols. In addition, we believe that appropriate benchmarking routines able to convert the temporal profiles from each joint into more discrete indicators will be tremendously useful for easy comparison across systems. Spatiotemporal parameters, by contrast, are a good example of standard metrics. They are able to grasp the main features of kinematic performance in basic locomotion tasks. Indeed, they would benefit from an appropriate combination with more complex kinematic and kinetic variables to fully characterize locomotion, in particular over complex terrains or in the presence of perturbations. Symmetry and coordination are two crucial aspects that are still poorly considered in the evaluation of exoskeleton performance. These aspects are highly relevant in the clinical field to evaluate the correctness of a patient's motion, and should therefore receive more attention in the future. The concept of human likeness, very relevant in other fields, for example humanoids or artificial intelligence, has not been considered by any of the reviewed works. We consider that this aspect would be beneficial for wearable robotics to quantify the similarity between machine and human motion, an important requisite of symbiotic behaviour.

In the *human-robot interaction* category, metabolic cost is often referred to as the main descriptor of interaction performance. However, in our opinion, this PI should not be considered alone. There are many other complementary aspects that should be taken into account when evaluating human-robot interaction. For instance, EMG analysis is frequently used to quantify the effects of a robot on muscle fatigue. There are other approaches that consider muscle activity analysis to characterize interaction, for example the use of musculoskeletal models to estimate biological joint torques. These research directions are particularly promising, in our opinion. Comfort is another important and popular indicator of human-robot interaction. If acceptable levels of comfort are not achieved, the chances of the robot surviving in the market are low, irrespective of the level of technical readiness. Interaction forces, despite their great potential to quantify the physical interaction between human and robot, have been poorly considered when evaluating lower limb exoskeletons. In our opinion, studying the correlation between interaction forces and subjective variables of comfort, for example pain, will be particularly beneficial to the field. The aspect of cognitive effort, very relevant in the clinical field, has been particularly overlooked by the literature. The same applies to ergonomics. These aspects, together with comfort, are key human factors behind user acceptance of the technology and should be given the highest priority by the community.

Lastly, safety should be considered. This is a primary criterion for any wearable robot, due to the unavoidable physical contact between the human and the robot. If safety cannot be proved, any other levels of functional performance become irrelevant, at least from the market perspective. This aspect is significantly under-represented in the literature, and should be seriously addressed.

C. Limitations

This review includes papers from a wide variety of use cases, which may considerably differ in their interpretation of "good" performance. For instance, the clinical effect is likely to be the main concern in gait rehabilitation scenarios. In the military or industrial contexts, the metabolic cost or other usability factors may prevail. Stability and robustness could be dominant in the case of assistance to paralysed individuals. This review did not focus on this domain-specific perspective, which is nonetheless an important aspect that should be addressed in future analyses and research.

As a further limitation, we did not distinguish whether a given metric describes exoskeleton and/or human abilities. We limited ourselves to enumerating the objective means to quantify the bipedal performance of the "human plus exoskeleton" system, considered as one integrated entity. Future works focusing on unveiling the contributions of the machine and its pilot to a given behavioural performance are encouraged.

Two publications, [41], [45], covered some usability aspects that were not included in our list of PIs, such as donning and doffing time, and time to change the battery. We consider that these aspects are relevant, and should be included in the human-robot interaction category.

V. CONCLUSIONS

This review revealed an exponential increase in the number of papers focused on the evaluation of robot-assisted locomotion, which demonstrates a growing interest from the scientific community in the benchmarking of exoskeleton performance. We found a great variability in the variables and experimental setups proposed. If on one side this lack of uniformity impedes the performance of direct comparisons across robots, on the other side, the rich pool of methods and tools here collected represents a solid scientific basis on which a benchmarking methodology can stand. Almost half of the papers reviewed focused on walking on flat ground or a treadmill, which highlights how the exoskeleton community is still very focused on basic locomotion skills. Other motor skills are receiving increasing attention but still cannot be considered to have reached the same level of maturity. Standing and balance skills have been greatly overlooked in the literature, together with other essential motor skills such as walking on irregular terrain or in the presence pushes, turning, and lateral stepping. We consider that it is extremely important to test all these functions to demonstrate high levels of readiness in out-of-the-lab environments. Among the performance indicators (PIs) considered, kinematic/kinetic metrics, together with simple indicators based on distance and time, were extremely popular. We observed a general trend towards human-robot interaction indicators when evaluating straight walking, but these indicators were poorly considered when assessing other motor skills. A more comprehensive application of these metrics would be beneficial in order to permit an appropriate comparison of exoskeletons across the different motor skills. In particular, the aspects related to symmetry, coordination, versatility, ergonomics, comfort and stability to external disturbances need to be explored more intensively to demonstrate the ability of a wearable robot to act symbiotically with the human. Lastly, safety, as a primary requirement of any assistive, rehabilitation or augmentation device, should also be taken into consideration more rigorously when evaluating exoskeleton prototypes.

The results of this review can be taken as a starting point for the development of a unified and standardized benchmarking scheme and drive the wearable robotic community to demonstrate that our robots can meet real market needs.

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