Human-like arm motion generation: A Review

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Abstract: In the last decade, the objectives outlined by the needs of personal robotics have led to the rise of new biologically-inspired techniques for arm motion planning. This paper presents a literature review of the most recent research on the generation of human-like arm movements in humanoid and manipulation robotic systems. Search methods and inclusion criteria are described. The studies are analysed taking into consideration the sources of publication, the experimental settings, the type of movements, the technical approach, and the human motor principles that have been used to inspire and assess human-likeness. Results show that there is a strong focus on the generation of single-arm reaching movements and biomimetic-based methods. However, there has been poor attention to manipulation, obstacle-avoidance mechanisms, and dual-arm motion generation. For these reasons, human-like arm motion generation may not fully respect human behavioural and neurological key features and may result restricted to specific tasks of human-robot interaction. Limitations and challenges are discussed to provide meaningful directions for future investigations.

Keywords: human-like motion; humanoid robots; arm motion planning; literature review.

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1. Introduction

New questions inevitably arise during the design of novel Human-Robot Interaction (HRI) or Collaboration (HRC) paradigms and often concern the authority and the autonomy level of new intelligent devices [1]. Ethical and anthropological issues have been recently considered by the government of Japan with the initiative called Society 5.0 [2]. The latter is expected to be a technologically post-humanized society where humans and robots coexist in the same environment and work to improve the quality of life by offering customized services to cope with various needs. The new social paradigm differs from the current Society 4.0 by the fact that robots will not only be passive tools as they are nowadays. On the contrary, they are expected to be active agents capable of proactive data collecting, making decisions and friendly behaving to maintain human beings at the core of the society, but not alone within it. Due to the process of post-humanization that is taking place, this new anticipated society is significantly dependent on the emerging transformative technologies that will impact the interactions among individuals as it has never happened so far. For example, a humanoid robot can be considered a personal helper designed to respond to the needs of human beings. Such an *artificial man* [3] could carry and manipulate objects for people with disabilities, could replace some cognitive functions or take part in the educations of children. A robot with these features is human-centered because it is meant to interact, collaborate and work in unstructured environments with human beings [4]. For this reason, research in robotics and artificial intelligence needs to be necessarily enriched by different scientific disciplines such as ethics, psychology, anthropology and neuroscience to simulate or mimic life-like activities and appearance [2,4–6]. These new abilities in robots significantly influence how they are perceived by interacting human partners.

Studies have revealed a very positive attitude towards robots and the idea of being surrounded by them in different personal and societal contexts [7,8]. People commonly expect from robots a very pragmatic daily help in domestic, entertaining and educational applications. Moreover,

having intelligent devices that perform repetitive or dangerous tasks is desirable because safety and monotonousness seem to be the most important issues in industrial settings. Particularly, robotics in the upcoming industry 5.0 is expected to augment the capabilities of human workers instead of replacing them. The current industry 4.0 has been featured by robots designed for complete automation of workflows, while the industry 5.0 will include robots intended to satisfy the necessities of human co-workers for the augmentation of productivity and efficiency of an entire company [8]. Therefore, in this new human-centred robotics, augmentation will gradually replace automation with the introduction of novel artificially intelligent devices that enhance collaboration in shared workspaces. For instance, the fundamental principles of motor interpretation behind successful human-human joint actions can be used when adopting motion planning strategies [9–12]. Koppenborg *et al.* [13] showed that the predictability and the velocity of the motion in robotic manipulators significantly influence the performance of the collaboration with human partners. Specifically, high-speed movements increase anxiety and risk perception of human co-workers, whom, consequently, act unpleasantly and inefficiently. Therefore, time parametrization also plays an essential role in any motion planning process that is intended for human-robot interaction. Body motion in robotics has also been recently considered a language to communicate emotional states of social robots [14]. This study revealed that social robots for educational support had more significant impressions on learners with body language than without it. However, movements of robots without a social role are also interpreted as social cues by human observers [15]. Therefore, there is an automatic and implicit cognitive process for the attribution of mental states in robots to anticipate their behaviours, which is independent of their assigned purposes. For these reasons, designers of human-centred robots and roboticists of different areas of research cannot skip accurate strategies of motion planning to obtain socially acceptable interactions with humans.

In the past decade, the action research area (of the so-called "New Robotics" introduced by Schaal [4]) has been densely characterized with the proposal of a wide range of techniques for human-like arm motion generation. This review provides an overview of the primary studies on novel arm motion planners that are meant to enhance human-robot interactions and collaborations. Through the analysis and the assessment of the most recent studies, major limitations can be identified, and future investigations can be directed.

The remainder of the paper is organized as follows: in Section 2, the design of this review and the search methods are defined; in Section 3, the collection of the search outcomes is provided, and the results are discussed accordingly to the features of the proposed solutions; the paper ends in Section 4 with a discussion of the obtained results, and in Section 5 with a description of the open issues in the current literature.

2. Literature review

The aim of this paper is to provide a comprehensive background of human-like arm motion generation for robots by reviewing the corresponding most recent literature. An extensive description of different approaches and techniques is essential for the identification of the current issues and the definition of new activities of investigation. Special attention was put on the criteria used for the evaluation of human-likeness of the generated movements, on the tools and the robotic devices used for experimentations, on the physical nature of the applied methodologies, and on obstacles-avoidance. The reliability, the performance, advantages and disadvantages are analysed and generally discussed to summarize the modern state of the art in the generation of human-like arm motion.

Being the sources of the vast majority of peer-reviewed publications on human-robot interaction and, more generically, robotics, the ACM Digital Library, the IEEEXplore, the Scopus and the Web of Science were searched. The search terms that were used in the advanced boolean method are:
(TITLE-ABS-KEY (arm) OR TITLE-ABS-KEY (upper-limb)) AND (TITLE-ABS-KEY (human-like) OR TITLE-ABS-KEY (legible) OR TITLE-ABS-KEY (predictable)) AND (TITLE-ABS-KEY (motion) OR TITLE-ABS-KEY (movement) OR TITLE-ABS-KEY (trajectory)) AND (humanoid OR robot)

AND (planning OR generation) AND PUBYEAR > 2005 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "p") OR LIMIT-TO (SRCTYPE , "j")).

The sources published in peer-reviewed conferences or journals were included, while unpublished or non-peer-reviewed manuscripts, book chapters, posters, and abstracts were excluded. Moreover, anything published before 2006 was also excluded because the state of the art might not reflect the capabilities that robots have nowadays. For the sake of completeness, papers proposing methodologies tested only on simulated frameworks were included, as well as on real robotic platforms. The focus is on those methods and techniques capable of generating human-like arm movements on humanoid and generic robotic devices. The minimum inclusion requirement of the proposed planning techniques is the capability of producing arm and hand trajectories showing typical human-like characteristics, which have been widely analysed and described in psychology and neurophysiology.

3. Results

3.1. Overview of the results

The original search returned 156 results. There were 54 publications left after removing the duplicates across the databases and applying the inclusion and exclusion criteria described in Section 2. The included papers were published starting from 2006 and, therefore, concern the most recent research in the topic. Figure 1 illustrates how the publications are shared among the databases of search. Scopus with 61.11% of papers is clearly the primary source of knowledge. It is followed by IEEEXplore follows with 22.22%, Web of Science with 11.11% and ACM Digital Library with 5.56%.
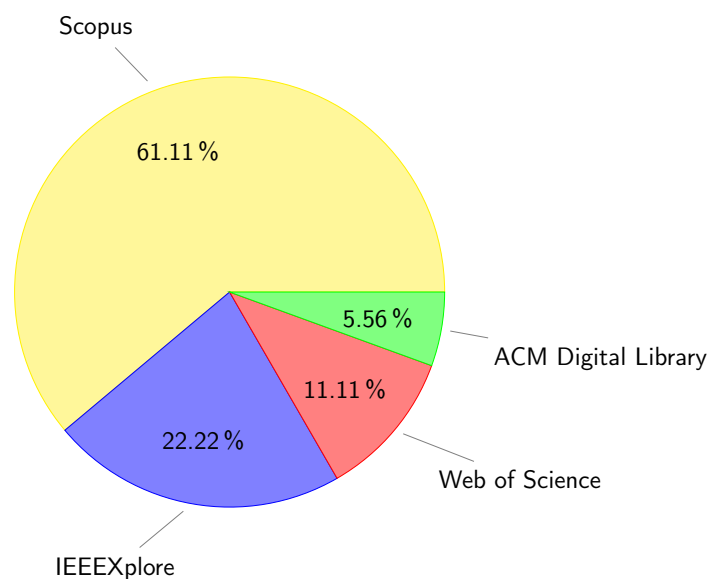
Figure 1. Pie chart showing the percentage of papers related to the databases.

The distribution of the publication venues is as follows (Figure 2): The International Conference on Intelligent Robots and Systems (IROS) was the largest provider with six studies. It is immediately followed by the International Conference on Robotics and Automation (ICRA) and the International Conference on Robotics and Biomimetics (ROBIO) with five papers each. Then, the International Journal of Humanoid Robotics (IJHR), the International Conference on Humanoid Robots (Humanoids), the International Conference on Numerical Analysis and Applied Mathematics (ICNAAM) and the journals of Autonomous Robots (AURO), Robotics and Autonomous Systems (RAS) and Intelligent and Robotic Systems (JINT) provided two papers each. The majority of sources delivered one paper. Among them, there is the International Journal of Robotics Research (IJRR), the Journal of Computational Science (JCS) and Frontiers in Psychology (FPsy).
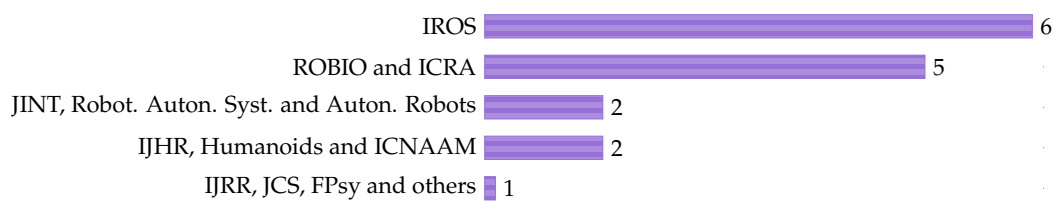
Figure 2. Bar chart showing the distribution of the sources of publication. Numbers indicate the number of papers per each source.

Before describing more in detail the selected studies, an overview concerning the experimental equipment is presented. The types of results were classified according to the robotic systems that were used to validate the proposed methods of human-like arm motion generation. This preliminary distinction is important to deduce implications regarding their level of applicability. For this purpose, the pie chart in Figure 3, illustrates the percentage of papers describing methods that were tested on robotic manipulators (37.03%), on humanoid robots (35.19%), and on simulations only (27.78%).
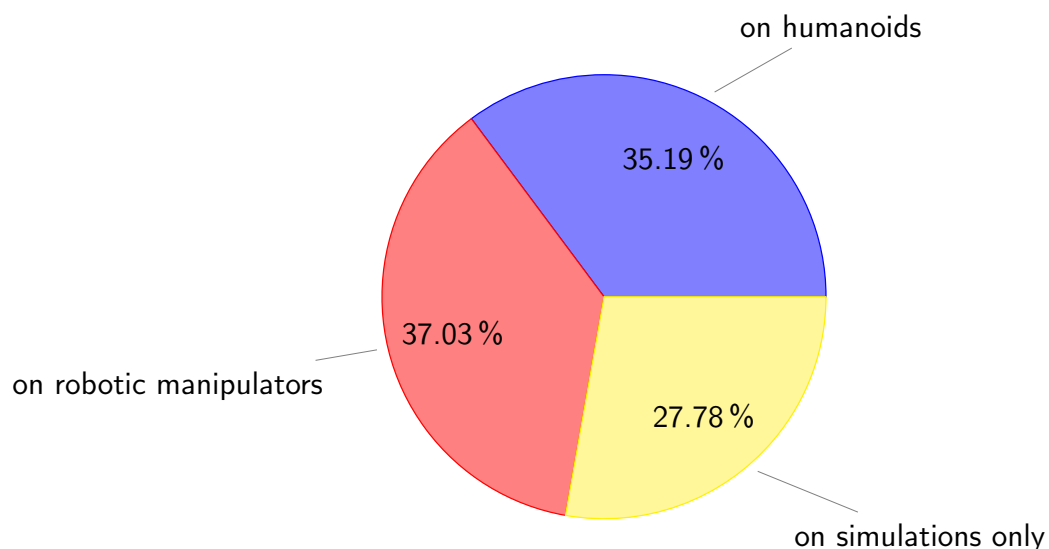
Figure 3. Pie chart showing the types of experimental results

Robotic manipulators and, in second place, humanoids are arguably the most preferred tool for testing and showing the level of human-likeness provided by different generation techniques. A humanoid robot can provide a high level of anthropomorphism that can be used to encourage interactions with human partners [16,17]. Figure 4 shows the anthropomorphic robotic systems that were utilized in the included studies. The *HRP-2* robot (Figure 4f), which was introduced by Kaneko *et al.* [23], is a humanoid robot equipped with legs and two 6-DOFs arms with grippers as end-effectors. It has been designed for cooperative works with humans; it is light and compact and has three CDD cameras mounted in the head. *HERB 2.0* [25], which is showed in Figure 4h, is a humanoid robot designed to operate with human partners in domestic environments. It is equipped with wheels, which allow the robot to navigate indoors, and with two Barrett 7-DOFs arms, each with a Barrett hand as end-effector. Moreover, it has an array of four laser scanners that provides clouds of 3D points in the surrounding environment. *MAHRU* [26] (Figure 4i) is a network-based humanoid robot with 35 degrees of freedom, 6-DOFs for each arm and 4-DOFs for each hand. It also has two 6-DOFs legs and can reach the maximum walking speed of 0.9 Km/h. A stereo camera mounted in the head, a microphone and four force sensors allow the robots to acquire knowledge of the current environment. *Simon* [27] in Figure 4j is an upper-torso humanoid robot with two degrees of freedom on the torso, two 7-DOFs arms and several degrees of freedom shared among the head, the neck, the ears and the eyes.
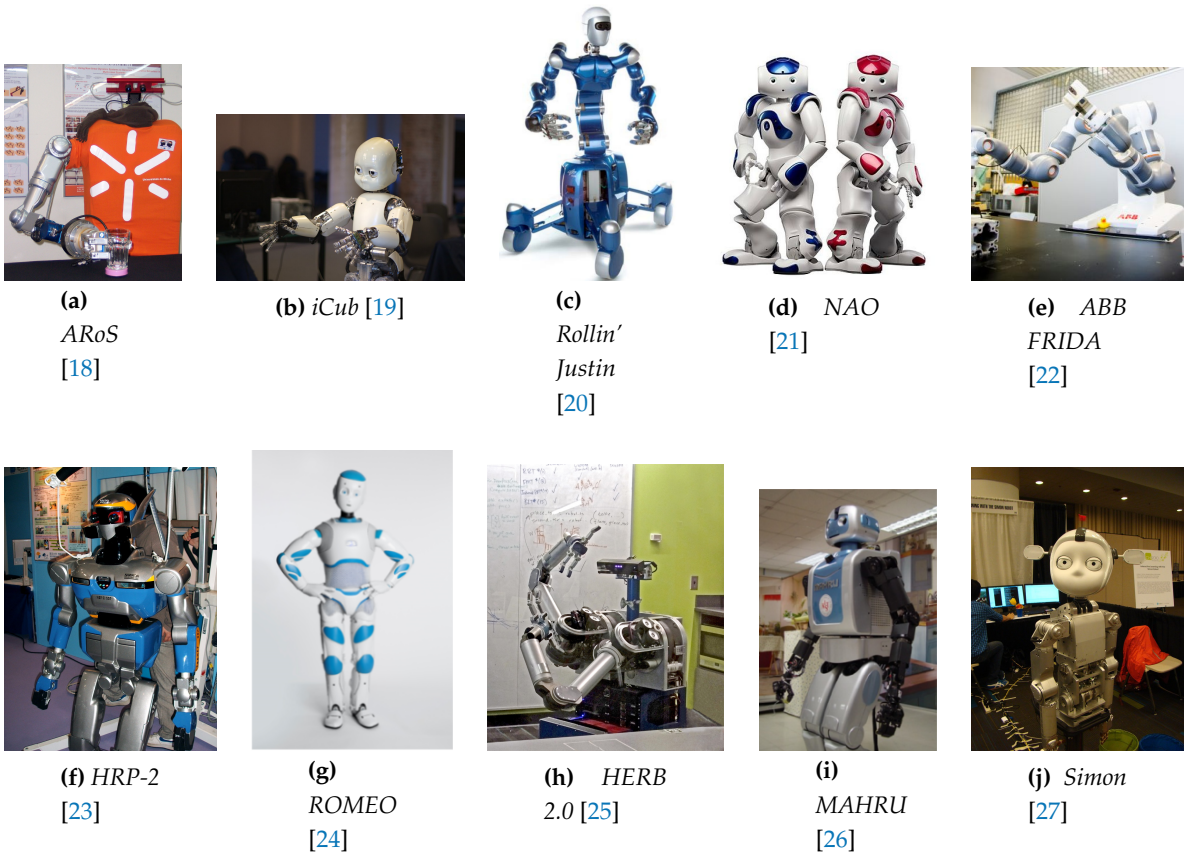
Figure 4. Humanoid robots used to test human-like arm motion generation. The images in this Figure are marked with a CC BY-SA 2.0 license (https://creativecommons.org/licenses/by-sa/2.0/legalcode).

iCub [19] (Figure 4b) was designed to have a high degree of manipulation. For this reason, each hand has 9 DOFs, and the arms have 7 DOFs. In total the upper torso has 30 DOFs. The robot is light with 22 Kg of weight, and the legs are strong enough to walk. Additionally, it has cameras, microphones and position/force sensors to obtain information about the workspace. *ARoS* [18] (Figure 4a) is an anthropomorphic robotic system composed by a static torso, two 7-DOFs lightweight Amtec arms with a three-fingered Barrett hand each and by a stereo vision system mounted in its head. *Rollin' Justin* [20] (Figure 4c) is a humanoid robot with 43 DOFs only in the upper-body and an omnidirectional torso driven by 4 wheels. *NAO* [21] (Figure 4d) is an affordable humanoid robot designed to adopt specific behaviours according to the needs of the user. It has a total of 25 DOFs of which 14 DOFs are in the upper body, with two 5-DOFs arms with 1-DOF hand each.

3.2. General insights on approaching human-likeness of arm motion

The procedures of human-like arm motion generation can be classified according to primary features that offer general but important insights on concepts, ideas and choices that are behind the genesis of a motion. A first classification addresses how the knowledge regarding the workspace of a robot is used to plan a feasible path. A method can be called *global* when the information of the entire workspace is processed off-line before the execution of a movement. On the contrary, *local* methods plan a motion on-line by taking into account portions of the workspace that are of immediate interest. This division is not always distinct, but, typically, these two approaches concern the implementation of strategies for the avoidance of collisions, when it is addressed. A second classification focuses on the physical nature of the variables that are involved in the motion generation process. Some methods are based on kinematic variables only (position, velocity and acceleration), while others also consider dynamical quantities (forces and torques). A proper selection of these physical variables defines the state space of a robot and might be driven by the expected interaction with the environment or with a human partner. However, the choice of considering *dynamics*, instead of *kinematics* only, is often influenced by biological motor principles when human-like motion generation is supported by discoveries in neuroscience. Regularities of human upper-limb motion can also be replicated on different levels concerning the space where a robot acts. Some applications may constraint the dimensionality of this space that consequently affects the complexity of a planning algorithm. For these reasons, a third classification concerns the space in which the generation of a motion takes place: it could be the *operational space* or the *joints space* of manipulation [28].

For example, Chen *et al.* [29] introduced a technique to reduce the dimensionality of the joints space for human-like dual-arm motion planning. This approach wants to replicate the demonstrations of human operators acting on common daily tasks. In particular, the replica of a bi-manual task of pouring water from a cup to another one was performed. The position and the orientation of human hands were mapped into the joints space of two 6-DOFs manipulators by inverse kinematics. Then, the configuration space (i.e., the joints space) is reduced to minimize the computational burden of the search of a collision-free path that is provided by the RRT-Connect algorithm [30]. Therefore, this approach works in the joints space of a manipulator; it runs off-line and globally deals with the workspace of the robot. Dynamical variables of the motion were not considered because Chen *et al.* [29] focused on the study of the non-linear relationship of the joints positions in the attempt of extracting this particular aspect of the human upper-limb motion.

An example of local planning in the operational space is described by Rano and Iossifidis [31], who presented an attractor dynamics approach for human-like hand motion generation. The authors considered the spherical coordinates (the heading directions and the velocity vector) of an end-effector to model human arm motion of reaching movements with a robotic manipulator. The proposed dynamical systems are based on attractive vector fields in the vicinity of a goal for the end-effector and repulsive vector fields for the obstacles in the workspace. Importantly, the attractor dynamics were properly designed to replicate the planarity characteristic of a human hand motion, which is also observed in scenarios cluttered with obstacles [32]. In other words, a straight-line solution

for the trajectory of the end-effector was analytically determined in obstacles-free scenarios where expectations on planarity were respected. However, to prevent unwanted collisions with obstacles, the trajectory could not maintain small values of torsion (i.e., good planarity) because the repulsion effects are significant only in the proximity of the obstacles and poor on other regions of the workspace [31]. A hybrid joints/operational-space approach based on dynamic movement primitives [33] was proposed by Lauretti *et al.* [34] to enhance functional anthropomorphism in redundant manipulators. In specific, Cartesian and joints-related characteristics are extracted from recorded human upper-limb movements during the execution of reaching tasks. The parameters of Cartesian and of joint Dynamical Movement Primitives (DMPs) are learnt from the recorded demonstrations and used to compute compatible desired trajectories in the operational and in the joints spaces. These references are coupled into an inverse dynamics controller that prioritizes operational-space constraints, while exploits the redundant variables of manipulation to replicate human recorded motion. Experiments with a 7-DOFs robotic arm and comparisons with classical Cartesian DMPs approaches demonstrated that the proposed hybrid method could provide acceptable accuracy in positioning and orientating the end-effector, higher levels of anthropomorphism within given physical joint limits and a successful obstacles-avoidance.

Dynamic models that simulate the capabilities of the human arm have also been used to generate biologically-inspired arm motion [35,36]. For example, Fu *et al.* [35] investigated how the motor synergies hypothesis behind the motion of human arms can improve planning reaching movements for a planar manipulator. Specifically, motor synergies are responsible for the activation of a group of muscles in a coordinated manner. Therefore, approaching control can be simplified by managing fewer variables corresponding to the synergies of a motion. The general planning strategy is formulated with a framework for optimal control that minimizes the contribution of the control activation inputs acting on the joints of the manipulator. Fu *et al.* [35] proposed the extraction of motor synergies from control inputs to solve the optimization problem in a lower dimensionality and, consequently, decrease the computational burden of the algorithm. Experiments on a 3-DOFs planar human-like arm moving on a bi-dimensional workspace demonstrated how the reduction of dimensionality generally improved the performance of planning by providing a higher success rate and a lower cost of the objective function spending less computation time. Further investigations on the properties of motor synergies showed their capability to adapt for the optimization of specific criteria, such as energy efficiency, jerk and smoothness of the resulting trajectory while achieving the intended goal of a movement.

Figure 5 illustrates a classification of the included studies concerning how the available workspace is approached, the physical nature of the variables that are involved in the planning process and the space of configurations. There is a clear predominance of global methods acting in the operational

(a) global vs. local methods   **(b)** kinematics vs. dynamics based methods   **(c)** operational space vs. joints space based methods
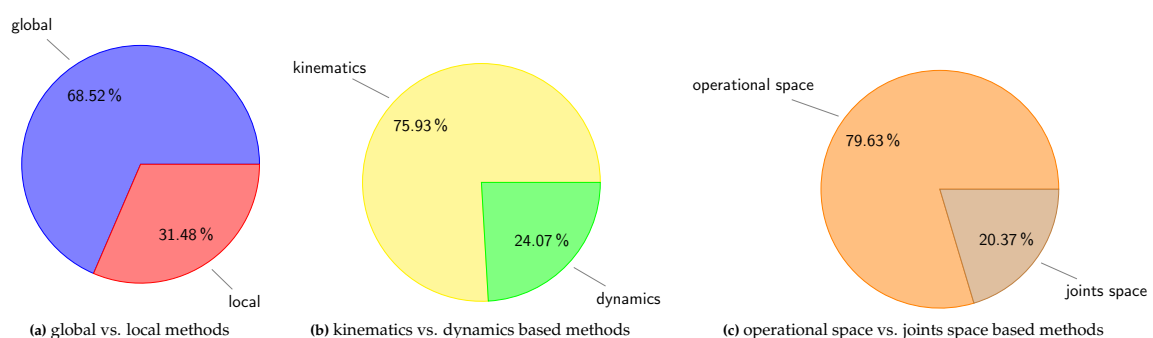
Figure 5. A preliminary distinction of the included studies

space and physically operating with the kinematic variables of a robotic device. Figure 5a shows that 68.52% of the included studies proposed global planning strategies, while only 31.48% of them treated the workspace locally. Modelling the workspace of a robot as a unique static environment generally simplifies the planning algorithms, permits taking advantage of the same assumptions in different

portions of the scenario and can generally replicate more loyal human-like regularities of the motion. On the contrary, local methods are generally more complex and can normally operate in dynamic scenarios accounting for on-line obstacles -avoidance. However, the risk of generating motion in local portions of the workspace is to lose the efficacy in replicating typical human arm motion features. As it can been seen in Figure 5b, 75.93% of the reviewed studies introduced techniques that operate with kinematic variables, while the 24.07% of them also considered the dynamics of manipulation. These findings are mainly due to the requirements of simplicity of the proposed solutions, and to the fact that most of the studies on human arm motion have been conducted on a kinematic level of the analysis. However, dynamic variables are necessarily introduced in biologically-inspired solutions that aim at replicating the muscles activities in humans. Moreover, the dynamics of a robotic agent is also needed in applications when specific physical interactions with the environment are required. The vast majority of the included studies presented solutions that operate in the operational space (79.63%) and only 20.37% of them in the joints space of manipulation (Figure 5c). Generating motion in the operational space generally means searching for a trajectory in a space with lower dimensionality than in the joints space. Additionally, patterns on human movements have been principally analyzed by considering the hand motion, which reflects properties on the end-effector trajectory in robotics. However, techniques that exclusively perform in the operational space may discard shreds of evidence of human arm movements that arise on different degrees of freedom, such as joint synchrony and a bell-shaped angular velocity profile [37–39]. A largely observed disadvantage of working in the joints space is related to a higher dimensionality of the search space that significantly influences the computational expense of the proposed solutions. For this reason, many authors introduced techniques of dimensionality reduction to achieve better performance without degrading the intended level of human-likeness.

3.3. From humans to robots

3.3.1. Applied principles of human motor control

In many and different ways, the included studies have considered human motor control in the construction of the proposed methods. For this reason, it is important to have specific insights into the principles and techniques that transfer human motion into robotics and assess the human-likeness of the generated movements. In Figure 6, the most relevant principles and metrics of human-like motion in robotics are illustrated. In this section, robotic applications are analyzed according to the popularity and originality of the human motor consistencies that support the proposed solution to the human-like motion generation problem.

Biomimetics

In the majority of the reviewed articles, human-like arm motion generation has been approached with techniques of biomimetics (51.85%). This particular set of solutions is based on the extraction of bio-markers and of physical regularities from recorded movements with the ultimate purpose of mimicking arm trajectories. For instance, Kim *et al.* [40] proposed a technique for deriving values of the *elbow elevation angle* from series of recorded human reaching movements in a three-dimensional environment. The *elbow elevation angle* (also called *swivel angle* or simply *elbow angle*) is the angle between the sagittal body plane and the plane formed by the triangle shoulder-elbow-wrist [40,41]. This angle features a human arm posture uniquely when the wrist is fully constrained in position and orientation. For this reason, it is the key human-like factor for transferring motion from human records to the humanoid robot MAHRU (Figure 4i). A trajectory is computed in the joints space by analytical inverse kinematics that considers six holonomic constraints concerning the position of the wrist, the hand palm direction and the *elbow elevation angle*, which encodes the human-likeness of a movement. Experimental results showed the similarity with the recorded human motion and the possibility of addressing real-time applications with the proposed solution. The latter was also upgraded with
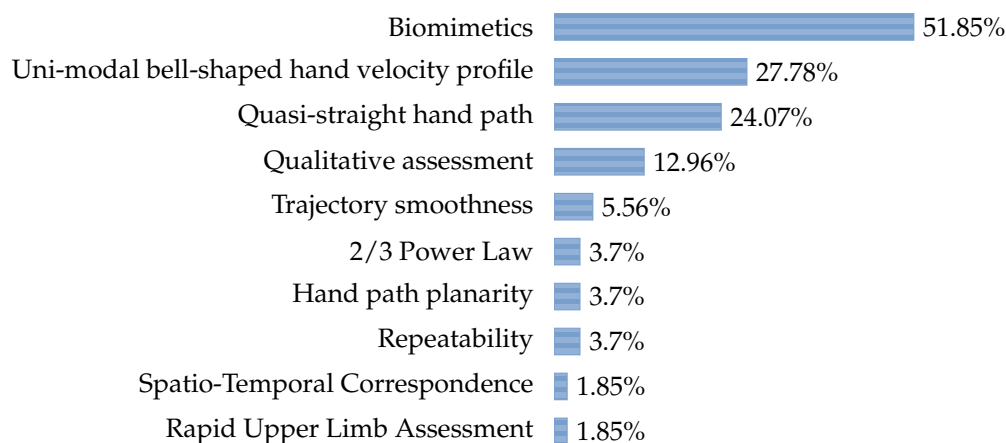
Figure 6. Bar chart showing in which percentage principles of human-likeness have been used for development and assessment in the included studies.

further functionalities that improve the communication with a human partner that might be moving in front of the robot [42]. Specifically, Kim *et al.* [42] defined the concepts of motion plane, which is the closest plane where the wrist trajectory belongs to, and of motion centre, which is the centroid of the wrist trajectory on the motion plane. Changing the direction of the movement is possible by aligning the normal vector to the motion plane applied in the motion centre with the desired direction that keeps attention on a human observer. Additionally, the *elbow elevation angle* and the magnitude of the wrist position are properly scaled to maintain human-like characteristics on the modified movement. Mimicking reaching and grasping movements was also addressed by Zhao *et al.* [43] through the minimization of the total potential energy of a human arm. The considered potential energy is the sum of a gravitational component, which is derived from the physical parameters of the arm, and of an elastic component that is obtained from acquisitions of human motion data on different subjects. Considering the planning of reaching movements, the minimization is permitted by the application of the Gradient Projection Method (GPM) that accounts for exploiting the null space of the Jacobian matrix [28]. The position of the end-effector is assumed to reflect a minimum jerk trajectory with null boundary conditions, which has been observed in human reaching motion [44]. Moreover, Zhao *et al.* [43] extended this solution to grasping movements by the introduction of a novel human-like arm motion planner that combines the advantages of the Gradient Projection Method in redundant manipulators and the RRT algorithm [45] (a GPM-RRT planner). A sampling-based planner like RRT allows to define a trajectory for the end-effector orientation, which is unknown a priori, and, most importantly, permits biasing the construction of a tree with optimal configurations provided by the GPM. Notably, in the case of grasping, further human data needed to be acquired to quantify how determined hand orientations affect wrist discomfort, which is defined as the distance from a comfortable wrist posture. Therefore, when the robotic arm acts on grasping not only minimizes its potential energy but also its wrist discomfort to mimic as close as possible human demonstrations. Qualitative observations on the human and on the robotic *swivel angle* trajectories showed the validity of the proposed planner in comparison with non-human-like alternatives.

One of the advantages of human-like arm motion planning based on biomimetic principles is the possibility of customizing movements on the characteristics of human operators. Expressing anthropomorphism by mimicking humans is arguably the most intuitive and direct way that roboticists have at their disposal, and probably, for this reason, biomimetic approaches are mainly preferred. Additionally, an efficient motion mapping from humans permits remote tele-manipulation in real-time when there is the need, for instance, to operate in dangerous or inaccessible environments. On the other hand, biomimetics methods require accurate and expensive motion capture systems that cannot

always be available, and complex post-processing frequently due to noisy signals and adaptation on different embodiments. Moreover, these methods are often tailored for the recorded human movements or specific manipulation tasks, even though some effort on generalization has been carried on by applying techniques of machine learning. A learned model often results very dependent on a task or a set of movements that compose a training dataset and, therefore, represent patterns that cannot be generalized on any human-like upper-limb behaviour. It is also worth noting that, while biomimetics focuses on joints-space patterns of human motion to encapsulate human-likeness, kinematic analysis of the human hand is often neglected in the generation of end-effector trajectories. However, many studies on human reaching and manipulation have shown specific regularities in the operational space of the human arm [46–48].

Kinematic assessment of the end-effector trajectory

It is state of the art that the human hand is typically featured by a quasi-straight path and a uni-modal bell-shaped velocity profile during reaching and prehension [46,47,49]. For this reason, many of the proposed solutions have taken inspiration from these psychological pieces of evidence to generate human-like arm motion. Specifically, the 27.78% and the 24.07% of the included studies, respectively, considered the hand velocity profile and the shape of the hand path to synthesize and assess human-likeness.

For example, Arimoto and Sekimoto [50] introduced a virtual spring-damper hypothesis for three-dimensional reaching movements of a 5-DOFs robotic manipulator that is driven by the Euclidean distance between the initial and the goal end-effector positions. This method extends a virtual spring hypothesis for bi-dimensional reaching movements and avoids the application of any inverse kinematics or dynamics to resolve the redundancy of the problem. Taking inspiration from the physiology of the human arm motion, Arimoto and Sekimoto [50] proposed to directly generate torque controls by the parametrization of stiffness and damping factors belonging to a virtual spring-damper system that connects the initial and the goal positions of the end-effector. Additionally, control signals are featured by passive damping on the joints of the manipulator and are influenced by the effect of the gravity force. Interestingly, the latter is estimated according to studies in handwriting control. The kinematic analysis of the generated reaching movements showed quasi-straight paths and single-peaked velocities profiles in the operational space. Acting on stiffness, different end-effector velocity peaks can be produced, while the shape of the end-effector path remains invariant.

A technique for time adjustment of the end-effector velocity was presented by Kashima and Hori [51]. Taking inspiration from observations of delays in human arm motion between the elbow and the shoulder, the authors proposed a modified minimum angular jerk principle for the optimal selection of this delay. This inter-joints time adjustment is designed to obtain exact symmetric end-effector velocities over a given duration of a reaching movement. This trajectory generation method was tested on a 4-DOFs simulated arm acting on a three-dimensional operational space, and it was compared with recorded human reaching movements and classical minimum jerk models. Investigation on short and lengthy distances from a goal position showed that the proposed trajectory formulation is featured by a symmetric uni-modal bell-shaped hand velocity profile and can replicate different curvatures of the human hand better than traditional methods that minimize the angular or the hand jerk.

An accurate replica of human hand positions and velocities during arm movements is strongly motivated by clear shreds of evidence in neuroscience and psychology. For this reason, many of the proposed human-like arm motion generation methods can synthesize these kinematic features by taking inspiration from different principles of the human upper-limb movements. Additionally, these techniques often take advantage of controlling schemas, which find applications when real-time requirements are needed. However, planning movements with kinematic constraints in the operational space is often intended for specific tasks and for reaching movements only, which transport the end-effector by point-to-point trajectories that ignore manipulation in the workspace. This is arguably

due to the inevitable constraints that manipulation introduces and that may negatively affect the kinematic analysis of human-likeness.

Qualitative assessment

A qualitative assessment for the synthesis and the evaluation of human-likeness of robotic manipulation was also taken into consideration by the 12.96% of the included studies. For instance, Dragan and Srinivasa [52] proposed an arm motion planning method that integrates the inferences of human observers to mathematically formalize principles of the action interpretation theory. Specifically, Dragan and Srinivasa [52] introduced the notions of legibility and predictability as opposite properties of the motion that stem from inferences of an observer. In a scenario with multiple potential goals for a movement, a motion is predictable when, given a goal, it matches human expectations. On the contrary, a motion is legible when permits an observer to quickly and confidently infer the correct goal. These concepts are translated into trajectory functionals for a constrained optimization that can plan predictable or legible arm movements in robots. Although the goal of the authors is not to explicitly generate human-like arm movements, the latter may be the outcome if this matches the expectations of a human observer. Legible movements, in particular, are intended to show the underlying intention of an action in ambiguous environments (with multiple potential goals) that might be shared with human partners. Thus, the integration of human inferences into robotic manipulation may significantly improve human-robot collaboration. Experiments with the robot *HERB* (Figure 4h) demonstrated the feasibility of the proposed planners and the exposition of the robot motion to human volunteers fairly supported the formulations of predictability and legibility in the domain of robotics.

The support from subjective ratings of robotic movements has also been used in combination with quantitative metrics of evaluation. For example, the trajectory planner described by De Momi *et al.* [53] finds support in different validating options. In specific, De Momi *et al.* [53] introduced a neural network based approach for robot-human handover tasks, which involves four independent neural networks (NNs) trained to learn the features of real human reaching movements towards evenly distributed goal positions in a three-dimensional space. After the training, the proposed solution is capable of predicting a human-like end-effector trajectory and its corresponding time of execution. Then, inverse kinematics is applied to transfer the motion to a 7-DOFs robotic manipulator. A qualitative assessment of the proposed solution was performed by recruiting volunteers for classifying an observed robotic movement as "biologically-inspired" or as "non biologically-inspired". In order to focus the attention on the end-effector and not on the motion of joints, the robot was covered and participants wore soundproof headset that mitigated the motor noise. Experimental results of this subjective ratings and of quantitative evaluations of human-likeness were in support of the proposed approach.

Collecting and analysing qualitative opinions of naïve subjects concerning the intention and the biological origin of a motion is certainly an easy and immediate manner of receiving descriptive feedbacks. However, the intrinsic subjectivity of such an analysis is the major drawback that induces the researchers to not only rely on it. Additionally, a qualitative assessment may also be misled by embodiment factors of the moving agent, which might distort the opinion of a human observer and contaminate the results. For these reasons, the number and the type of participants as well as the experimental protocol design are essentially important in user studies for the assessment of human-like arm movements in robotics.

Trajectory smoothness

While in classical motion planning techniques the smoothness of a motion is measured by the sum of squared velocities or accelerations along a trajectory [54,55], human-like motion requires jerk-based metrics. Only the 5.56% of the included studies considered such a validation to assess human-likeness with the generation of limited jerky movements. For instance, the movements generated by the solution from De Momi *et al.* [53] were also evaluated through a measure of jerk on the principal plane

of motion. Specifically, the sum of the squared norms of the jerk vectors in the path is normalized along the total time of execution and the length of the trajectory. This metric offers an independent index of smoothness for the detection of biological behaviours during the analysis of generic reaching movements [56].

The measure of the jerk of the motion provides a compact and intuitive manner to validate the smoothness of human-like arm trajectories. However, in many of the included studies this metric was totally ignored. It is also important the fact that a measure of the jerk cannot be the only tool of assessment, but it must be included in a multiple validation system. Otherwise, a null jerk motion, which produces a triangle-shaped velocity profile, might be wrongly associated with the smoothest human-like trajectory that can be ever generated.

2/3 Power Law

The two-thirds power law (2/3-PL) formulates the non-linear relationship that exists between the wrist velocity and curvature of human planar reaching movements [57,58]. This kinematic characteristic was considered by only the 3.7% of the included studies as a valid reference of human-likeness in robotics. For instance, the 2/3-PL was part of the set of metrics that De Momi *et al.* [53] used to support and consolidate the biological origin of the generated arm movements.
The two-thirds power law was also used for determining its impact on the perception of robotic motion in comparison with other levels of anthropomorphism [59]. In specific, Hugues *et al.* [59] designed a virtual car assembly scenario with different robotic platforms for the establishment of a small user study with naïve participants. Geometric inverse kinematics procedures on a given set of robots were modified to provide three parameters of anthropomorphism: namely, a base inertia, an end-effector inertia and the two-thirds power law. While inertia on the base and on the end-effector was simulated by spring-damper systems, the 2/3-PL was respected by forcing the end-effector velocity in accordance to the curvature of its path. A simple protocol was set up by questioning on singular perceived sensations and feelings, while a simulated robotic manipulator was watched moving its end-effector on a circling planar path. Results showed that the most influencing criterion was the end-effector inertia, which positively impacts on the perceived flexibility, naturalness and human-likeness of the generated motion. Consequently, these movements encouraged safety, less stress and willingness to work with a robotic partner. On the contrary, the impact of the 2/3-PL on the perceived motion was mostly neutral.

In general, the application of the two-thirds power law in the generation of biologically-inspired arm movements is relatively simple and can be eventually used to replicate common human tasks, like hand writing. On the other hand, the assessment of human-likeness in robotic motion may require the planning and recording of a significant number of arm movements with the corresponding kinematic features. The 2/3-PL is only exhibited by bi-dimensional human trajectories, but it was showed that introduces systematic errors in correlation with the overall shape of the path [48].

Hand path planarity

The planarity of the hand path is a characteristic of human upper-limb movements that also occurs in the presence of obstacles [32]. For this reason, the 3.7% of the included studies took operational-space planarity into consideration of human-like arm motion generation (Figure 6). It can be used to assess human-likeness, simplify arm motion planning and mimic human arm postures. For instance, Xu and Ding [60] presented a method for bi-manual transporting tasks that constrains the motion of the end-effectors to lay on separated planes and utilizes synergies to reduce the dimensionality of the search for a feasible movement. In specific, the definition of planes of motion in the operational space allows the control of the wrists by two virtual 2-DOFs manipulators that are attached on a torso-like structure. From an anthropomorphic arm, a virtual manipulator is obtained by restraining a wrist to move along different possible shoulder-wrist lines, which can draw planar curves in the operational space. Positional constraints between the left and the right arms permit to find an analytical solution to the

translation planning problem. While translations are planned, orientations are consequently stabilized to maintain a constant rotation matrix between the left and the right wrists and to keep contact with the transported object. Simulations demonstrated the feasibility of the proposed motion planner for bi-manual transportation tasks. Moreover, comparisons with conventional inverse kinematics methods showed more natural end-effector trajectories and the avoidance of awkward arm postures.

On the one hand, planar human hand paths in reaching and transporting tasks can be used to significantly simplify the arm motion generation problem to show human-like features. On the other hand, this simplification might only result valid on specific scenarios and movements. Moreover, a serious reduction of the search-space dimensionality might negatively affect other important aspects that are typically observed on human arm movements. For this reason, planar operational-space trajectories should be analysed in connection with other human-like metrics and should preferably emerge from independently applied human motor control principles.

Repeatability

The consistency and repeatability of robotic arm motion have been considered important human-like properties by the 3.7% of the included studies (Figure 6). For instance, Koskinopoulou and Trahanias [61] presented an observation-based imitation framework capable of replicating human arm movements as well as producing novel (unseen) actions. The proposed solution overcomes common correspondence issues that might affect standard learning from demonstration techniques by the employment of intermediate latent space representations. In specific, human actions are visually recorded, while robotic actions are kinesthetically taught. Then, these high dimensional spaces of action are reduced to bi-dimensional latent spaces by non-linear techniques of principal components extraction. During the training phase, these latent spaces are associated by the minimization of the errors between human and robotic trajectories pairings. After training, the reproduction of human movements is performed by inversely projecting the robotic latent space back onto its high dimensional action space in the respect of physical joints limits. Experimental results with a 6-DOFs robotic manipulator showed the feasibility of the described imitation framework on writing and pick-and-place tasks. The ability to consistently generate similar arm motions on the basis of human repetitions was quantitatively assessed on the reduced latent space as well as on the action space of the robot. The detection of irrelevant operational-space errors also exhibited the capability of repeating arm trajectories when comparable human trials are observed.

Methods that enhance repeatability during imitation can certainly generate human-like arm movements. However, there is a relevant risk of ignoring other characteristics that are typical of human upper-limb motion. While providing repeatable features can simplify observation-based learning and intensifies predictability, it can also seriously undermine human-like generalization capabilities. Similarly to biomimetic approaches, expensive equipments and complex post-processing might also be required to record human demonstrations and show consistency on different kinematic levels (e.g., velocity, acceleration, etc.).

Spatio-Temporal Correspondence (STC)

Taking inspiration from the chaos theory, Gielniak *et al.* [27] introduced the Spatio-Temporal Correspondence (STC) as a tool to synthesize and evaluate human-like motion. Similarly to biomimetics, the proposed algorithm starts from recorded human trajectories and brings together three procedures into a pipeline to generate human-like robotic movements. The first step produces human-like motion through the maximization of the correspondence in space and time with a reference trajectory extracted from human goal-directed activities. This correspondence emulates the local couplings of connected degrees of freedom that in biological structures like humans are exerted by groups of muscles. The attempt of coordinating a reference trajectory through spatial and temporal shifts is realized by the minimization of a measure of dissimilarity, which has been generally used for chaotic signals: the Spatio-Temporal Correspondence. After this step, the resulting human-like

trajectory is subjected to optimal control [62] to produce a certain degree of variance for the motion. This second step is motivated by the fact that humans rarely replicate the same movement twice, even when the same task is performed. Adding variance around the reference trajectory (from the previous step) preserves the original human-like characteristics and, most importantly, respects the constraints of the motion in the joints space. Then, the optimal control provides a variant of the reference trajectory within the physical limits of the joints and respects any eventual synchrony. The third step projects the torque control commands onto the null space of the Jacobian that maps forces on the end-effector to the torque on the joints. This projection guarantees that the variant joints space trajectory does not compromise the operational space constraints of the reference trajectory, like holding a cup or pointing an object. Several tests with the humanoid robot *Simon* (Figure 4j) demonstrated that mapped motion from humans is perceived more natural, and its intention is easier to identify when it is coordinated with the STC method. Further experiments showed the capability of the proposed method of recovering human-likeness even in the presence of imperfect embodiments (e.g., any agent kinematically or dynamically different than the original one) or of lost information during mapping (e.g., down-sampling of the trajectory signal). Adding variance to the generated human-like trajectories did not degrade the ability to recognize motion's intentions by human observers, and the variants exhibited the capacity of respecting both operational- and joints-space constraints. However, as expected, the performance and the ability to generate human-like variants of the proposed solution decrease as the number of constraints increases.

The Spatio-Temporal Correspondence is a versatile tool that can be used either to generate human-like arm movements or to quantitatively and objectively evaluate human-likeness. Another advantage is that the proposed solution is not heavily data-dependent because only one input trajectory is necessary for the generation of many possible variants around it. However, like for biomimetics approaches, there is the need for recording task-oriented human movements that often require the application of expensive equipments. This also means that for each constraint in the operational space (end-effector position and orientation), an input reference movement is needed and one of its generated variants has to be appropriately selected. Notably, the proposed method also risks undermining fluent real-time interactions with human partners because two optimization processes in the pipeline (first and second steps) may significantly slow down the generation of the final human-like motion.

Rapid Upper Limb Assessment (RULA)

Advances in ergonomics research have been an inspiration for novel human-like manipulation techniques that can also improve the performance of traditional motion planners in robotics. Zacharias *et al.* [63] proposed a solution that takes advantage of the RULA (Rapid Upper Limb Assessment) criterion to generate human-like configurations and towards a determined end-effector pose in the operational space of a robot. In ergonomics, the RULA criterion scores conditions of stress and strain of human arm postures on a range from 1 to 7 with lower scores identifying more natural and comfortable configurations. The proposed path planner is equipped with knowledge concerning the reachability of the workspace in a human-like manner. This knowledge is generated off-line and depends on the robotic agent that is applied for manipulation. In this particular study, Zacharias *et al.* [63] conducted simulations and tests with the robot *Rollin' Justin* that is illustrated in Figure 4c. The dexterous workspace is modelled by a capability map that is composed of discrete subregions where the end-effector can reach determined positions with different orientations. Each subregion includes spheres with a certain index of reachability, which measures the success rate in finding inverse kinematics solutions that place the end-effector onto uniformly distributed points on these spheres. Then, the restriction of the capability map to those robotic postures that possess acceptable RULA scores (usually no more than 4) provides a portion of that workspace that intuitively manifests the preferences of human manipulation. Given this restricted capability map, a RULA-driven inverse kinematics process (RulaIK) is proposed for reachable goal positions and orientations. While standard IK solvers depend on randomly selected initial arm configurations, the RulaIK iteratively try to solve

the inversion of the kinematics starting from human-like postures with limited RULA scores that interest the region in the vicinity of a goal. Compared with standard methods, the application of the RulaIK demonstrated to generate awkward postures with a significantly lower frequency. Moreover, the computed restricted capability map is also used to bias the sampling of a bi-directional RRT planner [30] by selecting arm postures in a preferred range of RULA scores and that are feasible configurations in the region between the start and the goal postures. Tests on pick-and-place tasks in comparisons with standard methods exhibited a faster convergence and smaller mean RULA scores over the resulting trajectories when the RulaIK was used in combination with RULA-biased sampling for path planning. Interestingly, a similar but slightly worse performance was achieved when the RulaIK was used in combination with uniform random sampling for path planning. This result shows the significant influence of a human-like goal configuration on the planning time and on the overall ergonomics of a trajectory.

RULA-driven arm motion planning provides human-like arm trajectories that can also be perceived natural because they are acting on a region of the workspace that is usually preferred by human operators. However, typical human time parametrization is ignored and, for this reason, the proposed planner might negatively affect human observations of a resulting trajectory. Although a faster convergence is achieved by the mean of RULA-biased IK and sampling, the total planning time is not compatible with the requirements of a fluent human-robot interaction. Additionally, the construction of a capability map with restriction on RULA configurations is robot-dependent and also adds a level of complexity that has to be negotiated with the level of accuracy in the discretization of the workspace.

3.3.2. Classification of the generated human-like arm movements

In this section, more insights regarding the type of movements that can be generated by the reviewed solutions are provided. Specifically, a proper classification is necessary to understand better the degree of applicability of the proposed techniques and how they should be upgraded for a wider generalization in different tasks. As the Figure 7 illustrates, 87.04% of the included studies addressed human-like single-arm motion generation, while only 18.52% of them proposed techniques for dual-arm motion planning. This outcome certainly depends on the robotic devices that are available for experimentation and on the tasks being addressed.
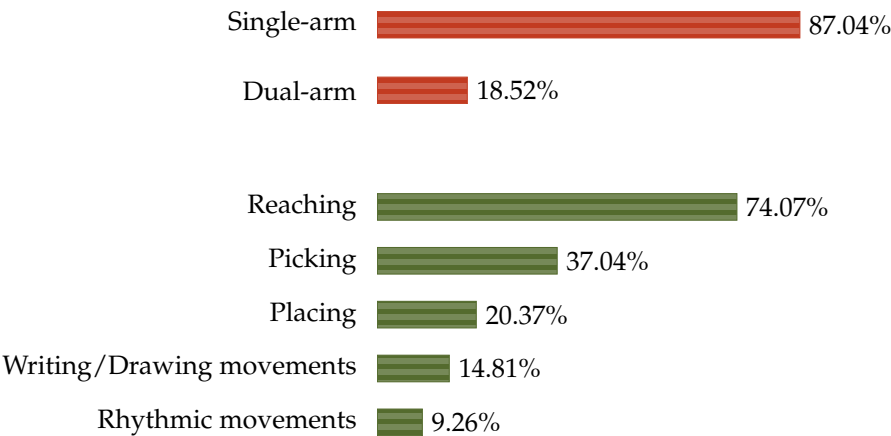
Figure 7. Classification of the human-like arm movements that are generated by the reviewed motion planners.

Featured by a limited degree of complexity, reaching (sometimes also called point-to-point) movements have been the focus of the 74.07% of the included studies. This category of movements generally transports an end-effector from one point to another point of the Euclidean space *SE* (3) without the engagement of any particular manipulation of objects. On the contrary, picking and placing actions of

the presented planners concern manipulation of rigid objects in the workspace of a robot. In particular, 37.04% of the reviewed papers addressed the generation of human-like pick movements, while 20.37% of them considered placing (Figure 7). Interestingly, most of the placing actions were part of the planning and execution of more general pick-and-place tasks.

A more specialized branch of robotics research in human-like arm motion generation has investigated planar movements for writing/drawing applications and the reproduction of rhythmic trajectories, which regards the 14.81% and the 9.26% of the included studies, respectively (Figure 7). The latter areas of research attract particular attention for their originality and vast unexplored future work.

For instance, Li *et al.* [64] introduced a trajectory planning method that can test different hypotheses concerning the role of the human Central Nervous System (CNS) in handwriting and drawing. Human actions seem to be represented in the CNS in more abstractive terms than with specific commands to the muscles [65]. For this reason, handwriting and drawing are encoded in terms of strokes in positions and directions without any specific motor command [64]. Specifically, three methods for imitating human handwriting and drawing are described: basic strokes, Bezier curves and non-gradient numerical optimization methods. The basic stroke method addresses the writing of alphanumeric characters with two basic elements (or strokes): circular arcs and line segments. Both of them are described analytically, and the inverse kinematics of a 2-DOFs manipulator is computed. The time parametrization of the resulting path is adaptable to different velocities profiles that can also simulate neurophysiological injuries and diseases. Concerning the Bezier curve method, Li *et al.* [64] took inspiration from computer graphics for the definition of a particular parametric curve, i.e. the cubic Bezier. This curve depends on four control points that are recorded after the visual acquisition of the image that has to be drawn. Then, a decoding process loads the saved parameters into a piecewise Bezier function that reproduces the handwriting. Finally, a trapezoidal speed profile is defined, and the end-effector motion is translated into specific joints-space commands. A variation of the Bezier curve method provides the non-gradient numerical optimization method that takes inspiration from vehicle guidance. Simulations with a three-links manipulator demonstrated the feasibility of the proposed trajectory planners in drawing complex figures mixed with alphanumeric characters.

Yang *et al.* [66] introduced a biologically-inspired method for the generation of cyclic (or rhythmic) arm movements that resemble the stability properties of animal and human motion. In specific, the neural oscillatory circuits on the spinal cord, which are known as Central Pattern Generators (CPG), are formulated into artificial neural oscillatory networks and combined with a virtual force inducer (VFI) acting in the operational space of a manipulator. The VFI interacts with a series of oscillators that operate on each joint influencing the corresponding torque. Particularly, each neural oscillator tracks the joint sensory signal feedback to exhibit an adaptive behaviour during interactions with the environment (the phenomenon of "entrainment"). The control scheme accounts for the joints space dynamical model of a multi-DOFs manipulator, which is featured by a PD controller in the operational space that follows a desired trajectory and by the scaled contribution of the rhythmic commands from the neural oscillators. Interestingly, the proposed scheme can achieve cyclic pattern generation without calculating the inverse dynamics and confronting the ill-posed problem of redundant systems. Simulations and experiments with planar and multi-DOFs manipulators demonstrated the capability of the proposed solution of generating smooth reaching movements, of producing cyclic repeatability of the joint positions and of adapting to unexpected environmental changes.

Being a relatively recent and trending topic of research, techniques of human-like dual-arm motion and manipulation are of particular interest. Some authors presented algorithms designed for single- and dual-arm applications [22,27,67], while others only addressed bi-manual planning problems [68–70]. Lamperti *et al.* [22] proposed a solution for resolving the redundancy of an anthropomorphic dual-arm robotic system through the minimization of muscular effort. With two 7-DOFs arms, the redundant variables raise from 1 in uni-manual motion to 8 in bi-manual motion when there are constant rules of inter-limbs cooperation with one object. The right hand posing problem is solved by minimizing the muscular activation that supports a manipulator against gravity with respect to given

operational-space constraints. The right arm configuration is uniquely identified by the hand pose and by an optimal swivel angle that minimizes muscular effort. A swivel angle, indeed, is the angle between the sagittal body plane of motion and the plane projected by the triangle wrist-elbow-shoulder, which is a key factor in featuring the human-likeness of a posture [41]. Then, the left hand posing problem is solved by considering the relative translational and rotational constraints with a given right hand pose. Similarly, the definition of the left arm posture is completed by the left swivel angle that minimizes the muscular effort of the left robotic arm. Addressing many samples of different dual-arm tasks, Lamperti *et al.* [22] fitted the data that relate arm configurations (14 variables) to the eight redundant variables that define the right hand pose, the right and the left swivel angles. Under the limits of the selected tasks, the fitting algorithm improves the performance of the proposed dual-arm redundancy solver because approximates the redundant variables by linear combinations of polynomial basis functions. Experiments with the humanoid robot *ABB FRIDA* (Figure 4e) showed the necessity of scaling the fitted functions according to the dimensions of the robotic manipulators. Results demonstrated the ability of the proposed method to generate human-like dual-arm movements when compared with those ones of a simulated bi-manual human kinematic model, which has spherical joints on the shoulders and the wrists.

Through the study of synergies in dual-arm manipulation tasks, Suarez *et al.* [70] designed a dual-arm human-robot mapping system that is based on the extraction of principal movement directions (PMDs) to simplify sampling-based motion planning in the joints space. Specifically, the positions and the orientations of the hands of a human operator are firstly recorded and sampled during the execution of an assigned assembly task. Then, these data are transformed into the operational space of a humanoid robot with two 6-DOFs manipulators equipped with a 16-DOFs hand each. Subsequently, the samples are translated into the joints space of the robot and the values of the joints are properly filtered to minimize their variance. The synergies of a particular task are then extracted as principal components of the dual-arm configurations that are the result of the mapping process. These principal components were called principal movement directions (PMDs) and represent the recorded dispersion of the samples. After the selection of feasible and collision-free dual-arm goal configurations, more instances of the RRT-Connect algorithm [30] are launched in a PMDs-subspace that reduces the dimensionality of the original search space (i.e., the dual-arm joints space). Experiments with assembly and free-movement tasks showed a significant increase of the planning computational performance when a minimal number of PMDs, which are sufficiently representative of the task-related human variance, is adopted.

In the same direction of research, Garcia *et al.* [71] proposed a synergies-based partition of the operational space for dual-arm reaching and grasping with a humanoid robot mounted on a mobile platform. The synergies represent a human-like coordination between the translational movements and the dual-arm motion of the robot that is approaching a region of the workspace for grasping two cylindrical objects on a table. Human motion is captured and used as reference for transferring human-likeness, which is maximized by an optimization-based human-robot mapping that ensures the correct placement of the end-effectors for a successful grasping. Then, principal components analysis is run on the space of configurations for the torso and the joints to extract a minimum number of synergies that significantly comprise the variance of the samples. This analysis permits to partition the torso translational space of the robot according to similarities of the captured dual-arm movements and, consequently, reduce the dimensionality of the planning search space for new joints-space states. For this reason, the proposed motion planner modifies the original version of the RRT-Connect algorithm [30] to take advantage of the acquired knowledge and considerably decreases the required planning time and iterations.

The vast majority of the included studies presented methods for the human-like generation of single-arm reaching movements, while poor attention has been put on drawing and rhythmic motion. More recently, more complex robotic applications of pick-and-place and dual-arm manipulation has started to attract the interest of an interdisciplinary research that takes inspiration from biological and

behavioural findings. Although more generic tools of arm motion generation that can offer human-like solutions for different classes of robotic movements are often auspicious, it emerged that research seems to be focused on narrow sets of applications. For instance, while more advanced solutions might potentially integrate simpler utilizations with few modifications, the techniques for planning human-like writing/drawing and rhythmic movements seem to be an isolated branch of investigation that can hardly be merged with more classical methods for reaching, picking and placing. Additionally, the great part of the included human-like dual-arm motion planners depends on biomimetic measures and on databases of human captured motion data that strongly limit task generalization.

3.3.3. Obstacles-avoidance in human-like arm motion generation

Endowing robots with the capability of avoiding and preventing collisions with obstacles in the workspace is a necessary skill in scenarios that are shared with humans for interacting purposes [1,3,4]. However, only the 27.78% of the reviewed papers addressed this particular issue. For example, Rosell *et al.* [72] proposed a human-like sampling of the configurations of a robotic arm-hand system that also improve the efficiency of a PRM-based graph building [73] in hand pre-shaping movements during grasping. Specifically, the hand motion of a human operator is captured during the execution of unconstrained movements and then mapped onto a robotic anthropomorphic hand to extract the inter-fingers coordination by a principal component analysis. Rosell *et al.* [72] also took into consideration human-like requirements that may regulate the palm orientation constantly facing an object to be grasped during prehension. These considerations, and the principal components of the fingers' motion, permit to solve a planning query between two feasible arm-hand configurations with reduced dimensionality. Simulations and tests with a 6-DOFs arm equipped with a four-fingered robotic hand demonstrated the feasibility of the presented virtually constrained planner. Additionally, comparisons with standard PRM planning showed that the proposed method can provide sequences of human-like postures with a higher success rate in a minor computational time.

Liu *et al.* [74] proposed an analytical inverse kinematics algorithm for anthropomorphic manipulators to map human-like configurations from recorded human arm motion data. In particular, the shoulder, elbow, wrist and palm points are operational-space key positions for a task-constrained human-robot mapping. While the shoulder positions is fixed at the base of a robotic arm and the palm/end-effector positions are dictated by the task, there is some flexibility in mapping the elbow and the wrist positions because only a grasping direction constraints the end-effector orientation. The proposed human-robot configuration correspondence solves the inverse kinematics problem with respect to the link lengths and the joints limits of the manipulator. In specific, the wrist key position is constrained to be on the line connecting the elbow and the palm positions (wrist-elbow-in-line) so that all the key positions lie on the same reference plane. Then, the obtained posture is iteratively adjusted if any of the joints limits is surpassed. This adjustment procedure starts by circularly moving the wrist position to obtain a feasible elbow joint angle. Next, the elbow key position is initially chosen to be the closest to the captured human elbow that lies on the reference plane. If any joints-space infeasibility is detected, then the elbow position is iteratively moved on an arc that defines different swivel angle values. The simulations with a 7-DOFs redundant arm demonstrated that the proposed IK method provides a high end-effector accuracy that slightly decrease in motion tracking but can show sufficiently rigorous human-likeness, which is manifested by the detected similarities with the human swivel angle. Interestingly, the human-like performance does not degrade when simple avoidance of a spherical obstacle is considered. The elbow key position is maintained, while the flexibility of the wrist is exploited to adjust the robot configuration and avoid collisions.

Although preventing self-collisions and avoiding obstacles in the workspace of a robot is a priority of human-centred robotics, the reviewed techniques of human-like arm motion generation rarely address it. Most of the proposed solutions for obstacles avoidance work under assumptions that significantly simplify a planning problem and take advantages of sampling-based motion planners that can surely provide collisions-free paths, but, on the other hand, require smoothing procedures and

neglect typical human-like time parametrizations. Additionally, experiments on collisions prevention often ignore assessing kinematic human-like features that characterize human arm movements [32].

3.3.4. Optimization, learning and control in human-like arm motion generation

Human voluntary movements are the physical linkage that the brain uses to communicate with the external world [75]. The movement generation system embodies the intentionality of a subject as the desire to change a portion of the surrounding environment, and the prediction of an action, which is based on learned internal models. The sensations and changes resulting from the execution of a movement feedback to the nervous system that might adjust the motion generation mechanisms. There is a complete specification of upper-limb trajectories before the beginning of the action, but there is also a continuous motion redefinition as an arm moves [75]. This implies that planning and controlling arm trajectories can be considered independent and interconnected stages of human-like arm motion generation [76]. The planning stage of volitional movements, in particular, is featured by optimality requirements when accurate prediction is necessary to satisfy the specifications of goal-directed actions [44,77]. As part of a more general feed-forward control policy, human motor planning also evokes "internal models" that are constructed by learning from prior knowledge and offer more precise expressions of an intended action [75]. Being part of a combined human motor framework, it is important to analyse optimization, learning and control techniques that have been proposed as solutions for human-like arm motion generation.

In the last decades, optimality principles and models have been studied and empirically developed under biological and psychological perspectives as a manifestation that features the evolution of the human motor system [78–80]. The 37.04% of the reviewed papers present different optimization-based solutions that consider the minimization of typical costs in human upper-limb movements. For instance, Albrecht *et al.* [81] applied bilevel optimization to imitate human reaching movements that were tracked and clustered during the execution of daily kitchen routines. In specific, a human-like arm trajectory is obtained by optimizing on two levels to address the replication of a wide range of movements. The resolution of a low-level problem comprehends the minimization of a weighted combination of three cost functions that have been experimentally observed in humans: a hand jerk cost [44], an angular jerk cost [38] and a torque change cost [77]. The resolution of a high-level problem finds the correct combination of the weights to minimize the distance between the optimal solution and the recorded human data in a single cluster. The availability of weighting factors permits adapting the cost according to the diverse tasks that identify the clusters. Simulations and experiments with the robot *iCub* (Figure 4b) demonstrated that the proposed method can correctly imitate human reaching movements better than the single optimal criteria alone, even though similarities can be limited by the embodiment of a robotic device.

In our previous studies, a human-like arm motion planning that minimizes the angular jerk of collisions-free trajectories was described [68,82,83]. Taking inspiration from psychological findings in human prehension [47], the proposed method is based on the resolution of two non-linearly constrained optimization problems. One for the selection of a goal posture, which ensures a correct collisions-free posing of an end-effector, and another for the selection of a bounce posture, which guarantees naturalistic obstacles-avoidance on the entire generated path. Then, the selected goal and bounce postures are integrated to compose a minimum angular jerk trajectory that endows a humanoid robot with the capability of manipulating objects in scenarios cluttered with obstacles. The goal and bounce postures selection problems are formulated in AMPL [84] and are solved by IPOPT [85], which implements an interior-point filter [86] for large-scale non-linear optimization. Simulations and experiments on assembly tasks with the robot *ARoS* (Figure 4a) demonstrated the feasibility of the proposed solutions in generating human-like single-arm movements [82], as well as bi-manual asynchronous [83] and synchronous [68] movements.

Training and learning models and processes in human arm-hand motion can describe how adult motor behaviour emerge [87] and how the information of actions can be memorized and stored in

internal models for generating prehension and manipulation [38,47]. The 22.22% of the included studies introduced techniques for learning and generalizing from the observation of human patterns of motion during the execution of particular tasks. For instance, Ga-Ram Park and ChangHwan Kim [88] described an optimal database construction of human re-targeted motion to learn arm motion primitives for a real-time human-like trajectory planning. Particularly, an Evolutionary Algorithm (EA) is applied as a global optimizer to iteratively select minimal joint torques trajectories among a collection of captured human motion data. The latter are clustered according to task-related conditions, which need to be respected for the correct accomplishment of an intended action. Within these conditions, the principal components of motion are extracted for a dimensionality reduction and for reconstructing new evolved movements that locally minimize the joint torque along the movement duration. Experiments with the humanoid *MAHRU* (Figure 4i) demonstrated that the proposed method is capable of learning minimal torque arm trajectories and generate human-like motion in real-time by reconstructing a movement through its principal components under given boundary conditions. The general performance decreases as the size of the clusters in the database increases because the selected principal components may not fully describe the variance of the captured motion. Taking inspiration from human adaptation to perturbations in reach-to-grasp movements, Shukla and Billard [89] introduced a coupled dynamical system to control the arm-hand interdependency during task execution. In specific, a Programming by Demonstration approach [90] is followed to learn the explicit coupling between the hand and the fingers motion during unperturbed and perturbed grasping actions. Human movements from different subjects were recorded, transferred to a robotic embodiment and modelled as Gaussian Mixture Models [91] for estimating operational-space position and velocities, which maximise the likelihood of the generated demonstrations. In particular, three joint distributions are learned to form the proposed coupled dynamical system (CDS): one encodes the dynamics of the hand transportation, one encodes the fingers motion and one encodes the state of the fingers inferred from the hand position. The norm of the distance between the hand position and its target represents the coupling function to deduce the state of the fingers, which activates a controller to update the values of the finger joints. When perturbations occur, tuning the controlling parameters can regulate the speed and the amplitude of hand reopening, which can either adhere to human-like requirements or surpass human physical limitations to cope with fast adaptation demands. Simulations and tests with the robot *iCub* (Figure 4b) showed the necessity of having an explicit arm-hand coupling for a successful grasping when, for example, a target suddenly changes after the onset of the motion and when a grip type needs to be substituted.

A deep neural network approach was proposed by Su *et al.* [92] to optimize the redundancy of anthropomorphic manipulators and reproduce the human-like features of human recorded motion. In particular, target poses and swivel angle motion are mapped from the given demonstrations with a network of five hidden modules, which apply convolution, a drop-out module to prevent over-fitting and a regression layer. After training, the regression model can predict human-like swivel angle kinematics from novel target end-effector poses. Then, the predicted swivel angle motion is fed to an inverse kinematics controller to reproduce human-like elbow positions through the redundant variables of an anthropomorphic manipulator. Simulations with a 7-DOFs robotic arm showed the capability of replicating human-like postures in tracking tasks. Additionally, compared with other artificial neural network based models, the proposed learning approach exhibited a higher reconstruction accuracy, a less predicting time and a greater noise robustness.

Studies in humans have shown that there is a complete trajectory specification before the onset of, for example, reaching and drawing movements. However, this specification continues throughout the motion and shows adaptations to unpredicted task-related variations [75]. Although visual information and, more generally, sensory feedbacks necessarily close a controlling loop, some evidences on humans concerning fast motion adaptation suggest the existence of feedback-free internal controlling models that emerge from experience [75,93]. However, accuracy requirements seem to be achieved by visually detecting a hand moving, which suggests motion modifications based on physical and environmental

sensations [75].

The 29.63% of the included studies introduced closed-loop controllers to cope with fast unpredicted changes that may occur in the workspace of a robot and to allow a compliant physical interaction with the environment. For instance, starting from the Virtual Spring-Damper controller introduced by Arimoto and Sekimoto [50], Bae *et al.* [94] took inspiration from the human muscle tension effect under gravity to increase energy efficiency and conform to a more repeatable human-like motion. Specifically, a torsional spring effect in the joints-space is added to the previous proportional derivative closed-loop controller, which ensures a correct trajectory tracking in the operational space. Feeding back a joints-space signal permits to privilege arm configurations, which are usually adopted by humans to minimize the tension of the muscles under gravity. Experiments with a 7-DOFs redundant manipulator revealed that the introduction of the muscle tension effect can reduce the average power consumption and trigger joints-space repeatability, which would otherwise be lost after a few repetitions. Moreover, it was shown that the proposed human-like controller is featured by compliant behaviours because it can promptly absorb external disturbances and maintain good operational-space tracking capabilities and joints-space repeatability. Stefanovic and Galiana [95] introduced a spinal-like regulator for replicating behavioural patterns that are typical in volitional reaching movements. In particular, this approach finds its foundations on the imitation of the centres of pattern generation that exist in the spinal cord and couple brain activity with the spinal motor areas. For this reason, the proposed controller is based on spinal-like circuits, which can exhibit intelligent functions that resemble internal models and reflexive reactions to external perturbations. The applicability of the proposed biological-like controller to multi-joint artificial limbs is tested using a two-links simulated robotic arm, which executes planar reaching tasks on different ranges of the available workspace. The results showed the capability of the proposed method of scaling the operational-space trajectories on spatial and temporal levels to fit with human-like arm motion requirements. In specific, the inherent spinal gains of the controller can be tuned to change the end-effector path curvatures and speeds to generate quasi-straight trajectories with bell-shaped velocity profiles. The regulator can also successfully absorb sustained perturbations and adaptively track moving targets to restore and maintain a human-like trajectory profile.

From the analysis of the included studies emerges a wide variety of optimization, learning and controlling methods that have been fairly applied for human-like arm motion generation. However, a common motor framework capable of an efficient modular integration seems to be still missing, even though roboticists have often referred to the genesis of movements as a linked functional decomposition of these technical features [76,96]. The proposed human-like arm motion planning and learning methods are generally based on task-related human captured data. They involve optimization techniques on a global level in the attempt of clustering motion patterns, and also on a local level in respect to human motion minimization principles. Learning approaches take advantages of dimensionality reduction mechanisms to simplify the generation process and extract synergies for a motion reconstruction in unseen environmental situations. Additionally, decision-making systems have also been presented as the result of learning from captured human data to select the most appropriate movement planning method. Although collections of human motor features guarantee an authentic source of knowledge and an unequivocal tool of comparison, these optimization and learning techniques may suffer from a lack of generalization because of internal models that store and feed experience in a categorical and human-dependant manner. Controlling human-like trajectories have also been studied to optimize the input motor commands of robotic manipulators. The reviewed controllers are of biological and behavioural inspiration and have been tested with devices of few degrees of freedom. Therefore, their application on complex human-like redundant circumstances remains unaccounted. The regulated trajectories are often generated on-line without any given reference from prior planning stages, even though the human Central Nervous System seems to generate optimized motion outputs close to a final motor solution before the onset of a movement [75,97]. Learning of control parameters and internal models are also absent in the analysed human-like

arm motion regulators, despite the fact that training and practice find neuroscientific and psychological bases in planning and controlling voluntary movements [98,99].

4. Discussion

A literature review on the most recent techniques of human-like arm motion generation has been presented. The analysis included 54 papers that were firstly classified according to the sources of knowledge and of publication. The vast majority of the papers was found in Scopus, immediately followed by the IEEEXplore, Web of Science and, with minor contribution, ACM Digital Library. Additionally, the conferences IROS, ICRA and ROBIO were the principal sources of publications, which were followed by prestigious journals in robotics. The equipment of the included studies was roughly equally composed by simulators, robotic manipulators and anthropomorphic platforms. The latter devices are of particular impact on motion planning solutions because provide a significant level of anthropomorphism that can positively influence interactions with humans [16,17]. The large majority of the reviewed papers proposed global methods that operate with kinematic variables and address the generation of trajectories in the operational space of robotic manipulators. This result might be due to the fact that a globally-considered static environment can provide solutions in a low dimensional space and a more accurate match with kinematic human-like features [47,49,100]. However, such methods might be reductive and risk to ignore human-like characteristics of the joints space, such as synchrony and bell-shaped angular velocity profiles [37]. Dynamics variables are often the focus of biologically-inspired solutions, which have been poorly addressed due to the difficulties that arise in transferring the muscles activities into robotic manipulators. Local human-like arm motion generation methods have also been scarcely proposed, but they can introduce the capability of simulating human reflexes and react to changing scenarios during the execution of a movement. However, these techniques only partially consider the workspace and, therefore, may fail to achieve human-likeness in complex tasks.

Roboticists have considered a variety of human motor control principles as inspirational and evaluational tools for proposing techniques of human-like arm motion generation. The included studies showed that researchers have mainly focused on biomimetic and human-robot mapping approaches, which can ensure a strong resemblance with human motion that is acknowledged as an objective reference of an action. In particular, human-robot transferring techniques can guarantee real-time execution of the movements, which is essential during tele-operation. However, most of these methods need expensive and complicated equipment for capturing human movements, databases to collect them and post-processing for features extraction. Additionally, these techniques generally lack of generalization because usually work for a limited range of goal-directed tasks.

Similar issues are also experienced by learning-based methods to teach specific tasks to a robot by imitation or training. Although learning from observations ensures a stable repeatability and a degree of adaptation to external perturbations, generalization is seldom achieved. The kinematics of the obtained end-effector trajectories have often been compared to the hand path and hand velocity profile of human reaching to show similarities and divergences between robotic and human movements. Most of these particular solutions were developed for single-arm motion and based on human-like optimization principles that minimize energy under tasks-related constraints. Manipulation in the workspace of a robot is often neglected when kinematics is assessed because of the inevitable complications that pick-and-place tasks would import into the analysis of human-likeness. The majority of the proposed methods were not tested with qualitatively assessments to understand the perception of human observers. However, there are many scientific shreds of evidence demonstrating that for pleasant human-robot interactions and collaborations, the movements of the robot have to be perceived natural, predictable and showing the intention of the underlying action without any verbal communication [12,101–103].

The smoothness of a trajectory has often been measured in relation with the third derivative of position, i.e., the jerk, which is a compact and intuitive index of human-likeness. However, smoothness is not

exclusively connected with jerk, but it must be assessed more comprehensively with other validation systems, such as, for example, the number of movement units [104]. The application of the two-third power law (2/3-PL) is relatively simple for the generation of biologically-inspired planar movements like writing or drawing. However, the 2/3-PL has shown to introduce systematic errors on the complete shape of a trajectory and needs to be extended to explain regularities of three-dimensional reaching movements [48]. Although path planarity in the operational space may significantly simplify a planning problem, this human motor principle should emerge from other independent human-like motor principles instead of being a constraint of the generation process. Otherwise, there is a risk of complicating a planning problem and decrease the overall performance. The repeatability of motion on imitating observed human movements can certainly increase predictability and simplify learning, but it can seriously undermine generalization on different tasks. With two optimization processes in sequence, the Spatio-Temporal Correspondence [27] can negatively affect real-time interactions with humans, but it is a versatile tool that can be used to either assess or generate human-like body trajectories from one single sample. Human-like arm motion has also been achieved by the RULA-driven technique [63], which introduced an upper limb assessment of the inverse kinematics and the sampling of the search space to enhance ergonomics, but ignored human-like time parametrizations.

Most of the included studies addressed single-arm reaching movements, while human-like dual-arm applications are emerging and pick-and-place tasks still deserve more attention by human-like arm motion generation methods. The simple nature of motion without manipulation and the vast literature concerning the psychology of human reaching have probably encouraged roboticists towards this direction of investigation. Replicating human writing, drawing and rhythmic movements revealed to be a small research branch, which seems to be isolated because not of easy integration with more classical methods of picking, placing, and reaching motion generation. The prevention of self-collisions and the avoidance of obstacles in the workspace of a robot were rarely considered in the reviewed papers, even though these are necessary features for interacting devices in human-centred environments. Additionally, many of the proposed solutions ignored a human-like kinematic analysis during the avoidance of obstacles and addressed collisions prevention under simplifying assumptions, which reduce their range of applicabilities.

Roboticists have usually defined the genesis of human-like motion as a connected system of different functional modules [76] where optimization, learning and control are integrated. However, the included studies do not refer to a common framework of motor generation for optimizing human motor models, learning internal models and control on external disturbances. On a local level, human motor minimization principles are applied, while learning techniques are used for clustering motion on a global level, for extracting regularities of captured human movements and for implementing decision-making settings. Studies have shown that the synthesis of motor solutions happens in the Central Nervous System before execution [75]. However, the reviewed controllers act in the absence of prior optimized trajectories that may guide the process of on-line regulation. Moreover, these controllers are applied to a few degrees of freedom and remain to be tested on more complex redundant manipulators and interacting tasks.

5. Conclusions

The limitations of the discussed literature on robotic human-like arm motion generation show the necessities of investigating comprehensive solutions, which can benefit from generalization capabilities for a wide range of tasks, types of movements and scenarios. The intentionality of motion needs to be encoded because it plays an essential role during interaction and collaboration between robots and human partners. More focus is needed on manipulative features and on obstacles-avoidance mechanisms that do not degrade the level of human-likeness with the increase of the complexity of a given task. For instance, behavioural studies show that collisions between the upper-limbs and objects in the environment seem to be anticipated and prevented through specific via postures during grasping [47,105]. For this reason, the generation of collisions-free arm trajectories in robotics

should take inspiration from similar techniques of human obstacles-avoidance instead of relying on non-human-like solutions, such as sampling-based path planning algorithms. Additionally, it emerges the necessity of having quantitative and qualitative means of assessment to obtain objective and complementary information concerning the human-likeness of robotic trajectories. Many of the reviewed techniques mainly referred to either task-related metrics or biomimetics, which might mismatch with the perception of human interacting partners during the applications on different situations. Further investigations on dual-arm human-like motion generation should be also addressed and perceived as an extensive branch of the single-arm counterparts. Many of the reviewed solutions to the bi-manual planning problem refer to mapping configurations of fixed-structures, instead, which show a lack of flexibility and of merging capabilities with single-arm tasks. Human principles of optimization, learning and control should also find place in a modular framework where a continuous and smooth interaction is enhanced to mimic the functioning of the Central Nervous System and respond with the challenges of the human-centered robotics [75,76,96].

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