Closure to "Discussion of 'A Review of Intent Detection, Arbitration, and Communication Aspects of Shared Control for Physical Human–Robot Interaction'" (Losey, D. P., McDonald, C. G., Battaglia, E., and O'Malley, M.K., 2018, ASME Appl. Mech. Rev., 70(1), p. 010804)

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In their discussion article [1] on our review paper [2], Professors James Schmiedeler and Patrick Wensing have provided an insightful and informative perspective of the roles of intent detection, arbitration, and communication as three pillars of a framework for the implementation of shared control in physical human–robot interaction (pHRI). The authors both have significant expertise and experience in robotics, bipedal walking, and robotic rehabilitation. Their commentary introduces commonalities between the themes of the review paper and issues in locomotion with the aid of an exoskeleton or lower-limb prostheses, and presents several important topics that warrant further exploration. These include mechanical design as it pertains to the physical coupling between human and robot, modeling the human to improve intent detection and the arbitration of control, and finite-state machines as an approach for implementation. In this closure, we provide additional thoughts and discussion of these topics as they relate to pHRI.

We agree that mechanical design is an important consideration when developing robots for tasks that involve shared control and physical human–robot interaction. In particular, robots that are working in close proximity to humans should be lightweight and compliant, so that—if an unexpected collision occurs—the human is not injured. Series elastic actuators (SEAs) have accordingly emerged as a desirable design element for pHRI. SEAs incorporate a compliant element between the actuator and the load, which beneficially reduces the robot's output impedance across the frequency spectrum. Interestingly, the mechanical design of SEAs contributes to all three aspects of shared control. By measuring the displacement of the compliant element, we can use SEAs to determine and control how much force the human is applying, which lends itself to both intent detection and communication. Moreover, by changing the position of the actuator as the human interacts, we can adjust the perceived stiffness of the SEA: this allows us to adjust the arbitration between human and robot. Recently, our research group has focused on determining the range of stiffnesses that an SEA can safely render to a human user, as well as developing control strategies to augment this range for both feedback and arbitration [4,5]. In summary, SEAs are an example of effective mechanical design for shared control applications, and—by their nature—SEAs enable intent detection, arbitration, and communication for pHRI.

Schmiedeler and Wensing bring up the importance of modeling, particularly as it is useful to intent detection and arbitration. We strongly agree and would like to emphasize here how physical modeling of the human, robot, and the interface between them can bring about improvements in the state-of-the art for almost all of the areas discussed. Model-based control of rigid robotic manipulators is foundational to the field and has been extended nicely to more flexible robots intended to work alongside humans [6]. As we experience a shift in wearable robotics from rigid to more soft and flexible designs, the challenges of physical modeling seem to expand at the pace of design innovation. Whether the application involves flexible cable-based actuation or soft pneumatic actuation, accurate and robust physical modeling of the actuation and mechanical design is a necessary step in our development of controlled physical interactions between human and robot that are safe, reliable, and effective. On the human side of modeling, new tools such as OPENSIM [7] facilitate modeling of the biomechanics of the musculoskeletal structure, opening up the black box that connects externally measured kinematic and kinetic data with internal muscle and joint loading and even individual muscle excitations as could be measured through electromyography. It is the authors' hope that the field will find such models of the human neuromusculoskeletal system increasingly useful in detecting difficult-to-measure variables of human intent, experimentally validating existing model-based approaches to wearable robot design, and increasing the specificity of the regulation of human effort during arbitration for applications such as rehabilitation.

Schmiedeler and Wensing have also pointed out that finite-state machines can be leveraged to detect the human's intent or to change the arbitration during shared control. This is especially true when the human's intent—or more generally, the human's objective—belongs to a discrete set of possible objectives. In work by Javdani et al. [8], the human's objective is a goal position, and the robot has a belief over the space of possible goals. As the human takes actions toward their desired goal, the robot updates its belief, and takes actions to maximize the robot's expected reward. Later works considered the effects that robot actions can have on the human's objective: if the human is willing to adapt, the robot can take actions to convince the human that their current goal is suboptimal, and then cause the human to switch to the optimal goal. Knowing that the human has a discrete set of possible intents makes these problems tractable and allows us to implement finite-state machines to learn the human's intent in real time. Finite-state machines can also be used to switch between different levels of autonomy—but we must be careful to ensure that these changes do not destabilize the system. Although finite-state machines are a reasonable starting point, moving forward we expect that shared control systems for pHRI will increasingly work in continuous intent and arbitration spaces. For example, the human may be happy with the robot's goal position, but unhappy with the robot's trajectory

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[9]. Learning the human's intent within continuous spaces is accordingly an active research topic.

In closing, as robotic systems become increasingly present in spaces and environments shared with humans, we see a rise in the number and type of applications that rely on physical coupling between robot and human. To better understand the shared control architectures that govern pHRI, we have introduced a three pillared framework of intent detection, arbitration, and feedback/communication [2]. Often, the implementation of these aspects of a shared control system depend on high quality mechanical design of the physical coupling between robot and human, informative models upon which we base on control actions, and finite-state machines to carry out the intended actions of the coupled system, as highlighted in the discussion prepared by Schmiedeler and Wensing [1]. With further research, the potential for fluent and effective pHRI in an ever growing range of applications is clear.

References

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