Chapter 19
A Review on Magnetorheological Fluids and Its Application in Lower-limb Prosthetic Devices

Aayushi Soni, R. Sujithra, and R. P. Tewari

Abstract Magnetorheological fluid is a field-responsive material. The rheological properties of magnetorheological fluid can be precisely controlled and reversed. This change in rheological property controls the damping force by an externally applied magnetic field and makes them suitable for automotive, structural, manufacturing, and military applications. In the last two decades, it has gained a significant impact in the field of intelligent healthcare devices. Various biomedical devices had been developed to mimic and restore the gait cycle for the amputees. However, MR-based devices provide real-time controlled damping to improve the gait cycle. This review briefly discusses the tailor-made properties of magnetorheological fluid based on their constituents and stabilization methods. And, it also addresses the significant contributions of magnetorheological fluid in the lower-limb prosthetic devices.

Keywords Magnetorheological fluid · Prosthetic devices · Semi-active devices

Introduction

Magnetorheological fluid (MRF) is a type of controllable fluid. It can change its rheological and damping characteristics under an externally applied magnetic field [1]. This effect is called as magnetorheological (MR) effect. MR fluids are suspensions of magnetizable particles and a carrier fluid. It exists in a liquid-like state, in the absence of magnetic field (off-state). When the magnetic field is applied, it creates strong interaction between the particles due to the magnetic dipole–dipole interaction. This leads to the formation of chain-like structures in the direction of the applied magnetic field and results in solid-like behavior (on-state). Thus, it creates the resistance to flow and induces yield stress of about 50–100 kPa. This process is reversible with a response time of few milliseconds [2]. When the magnetic field is off, or the shear stress exceeds the yield stress, it reverts to the off-state viscosity [3].

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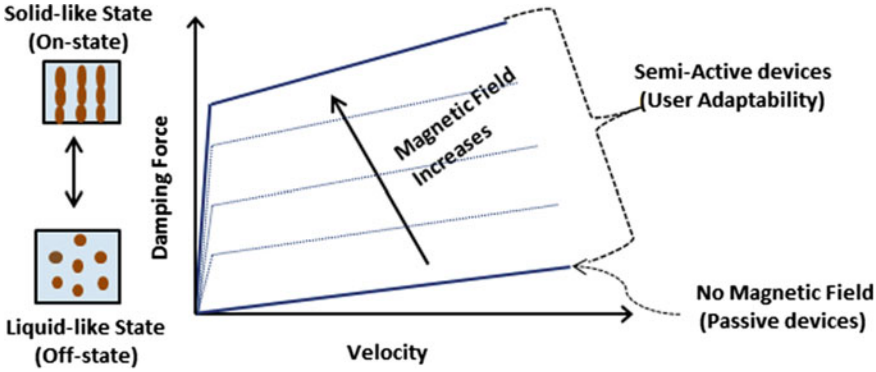

Fig. 19.1 Typical magnetorheological fluid

MR fluid-based devices act as a damper to suppress and control the undesired shocks and vibrations in real time [4]. It is well-known that passive devices are only effective at narrow operational conditions. However, semi-active control system combines the feature of the passive device consistency and tunability of the active device. MR fluid dampers can be able to change its damping/rheological characteristics by controlling the magnetic field intensity using a suitable control strategy, and so, it acts as a semi-active devices. Due to reversible rheological properties of MR fluid, it can meet the dynamic damping forces and can transmit torques as per the device requirements [5]. So, they are called tunable or adaptive devices. Magnetorheological fluids have been used in several devices like rotary brakes, seat dampers, clutches, mounts, polishing machines, prosthetics, haptic, and rehabilitation [6]. The devices that make use of MR fluids are more consistent than the conventional electromechanical devices. MRF devices can operate with low power consumption, and their typical operating voltage and current are 2–25 V and 1–2 A [7] (Fig. 19.1).

MRF devices can operate using different modes such as flow mode (used in damper and shock absorber), shear mode (used in clutches and brakes), and the squeeze mode (used in impact dampers) [2, 8]. The multiple or mixed flow mode produces higher damping forces than a single flow mode [9]. The MRF damper configuration also plays a significant role when subjected to shock and impact loads [10]. The performance of the MR fluid depends on the type of the device, actual operating conditions, and stability of the fluids [11]. The advantage of employing MR fluids in prosthetic device helps to absorb the shocks and improves the gait stability. It can act as an artificial muscle to support the biomechanical function similar to a healthy human limb. This article reviews the MR fluid properties and its applications for the lower-limb prosthetic devices.

MR Fluid Materials, Properties, and Stabilization Methods

MR fluids are uniform dispersion of particles in the carrier fluid. It is prepared by mixing of micron-sized magnetizable particles with a carrier fluid. The induced yield stress in the MR fluid depends on several factors such as the size, shape, density, volume fraction, and magnetic saturation of the particles, the viscosity of carrier fluid, and the strength of the applied magnetic field. MR fluid experiences some drawbacks, such as sedimentation and clustering, which restrict the long-term usage and efficiency of the device. Sedimentation arises due to the density mismatch of magnetic particles and the carrier fluid. And, the magnetorheological effect also decreases with the sedimentation rate. The magnetic particle size and shape also play a critical role in inducing the yield stress, and it is also responsible for the erosion and friction effects [12]. As the particle size reduces, the saturation magnetization of the magnetic particle also decreases [13]. For a better MR effect, the magnetic particles should have the highest saturation magnetization. Generally, soft magnetic materials possess low coercivity and low remnant magnetization. So, it is easy to control the reversible rheological characteristic [14]. Carbonyl iron particle is a soft magnetic material with the purest form of iron of about 97.5–99.5%, which is the most commonly used magnetic particle in MR fluids. It also has the highest saturation magnetization and low coercivity [15]. The flake-shaped carbonyl iron-based MR fluid has superior sedimentation stability compared to spherical-shaped particles [16]. Rod-shaped microwires result in higher yield stress and improved stability than the spherical-shaped particles [17].

As the particle interacts, friction heat is generated and leads to an increase in carrier fluid temperature. The operating temperature range of MR fluid-based devices depends on the rheology, tribology, and volatile characteristics of the carrier fluid [2]. Besides, the carrier fluid should also possess good chemical and thermal stability. High-viscosity carrier fluid material is preferred to improve the sedimentation stability. However, the low-viscosity carrier fluid supports the redistribution of particles and also increases the MR effect [8]. Most of the MR fluid uses silicone oil or hydrocarbon oil as a carrier fluid. For longer duration, exposing silicone oil at high temperatures results in thickening of fluids [2]. Different types of carrier fluids are polymeric compounds [18], water–oil emulsion [19], ionic liquids [20], and shear thickening fluids [21], which significantly reduce the sedimentation with certain limitations in usage. The polymeric compounds are used as a carrier fluid to enhance the MR effect but increase the off-sate viscosity [18]. However, polymer carrier fluid with high molecular weight reduces the system stability [22].

Due to remnant magnetization, the iron particles agglomerate to form a hard-cake. The most common techniques to inhibit the sedimentation process in MR fluids are particle coating, adding nanoparticles, or adding suitable additives in the carrier fluid. Adding surfactants can prevent the clustering, rate of settling of the magnetic particles in the off-state, and the thickening of fluids after multiple cycles. The addition of magnetic nanoparticles in the MR fluid helps to prevent the agglomeration process in the off-state. Nanoparticles are dispersed in the voids of the regular chain of the micron-sized particles and hence increase the yield stress [23]. Adding fumed silica in MR fluid also prevents sedimentation [24]. Coating the magnetic particles is one of the effective stabilization techniques but reduces the yield stress. Carbonyl iron particles coated with PMMA show a smooth surface with increased dispersion stability, as it decreases the particle density. The polymeric coating lowers the friction factor but increases the distance between the particles in the on-state, decreasing the MR effect [25]. The core (carbonyl iron)-shell (PMMA) structure of magnetic particle leads to lower density and improves the dispersion stability but with no significant change in MR effect [26]. Coating the carbonyl particle with multi-walled carbon nanotubes reduces the magnetic saturation slightly but improves the sedimentation stability [27]. Carbonyl iron/polystyrene composite particles improve sedimentation stability and also provide a good MR effect [28]. The iron nanowires can also add along with the carbonyl particles to enhance the yield stress and stability [29]. The degrading properties of MR fluid depends on operating conditions such as shear rate, temperature, and duration. The above discussion shows that MR fluid properties can custom made to optimize the MR effect with improved stability.

Application of Magnetorheological Fluid in Lower Extremity Prostheses

Prosthetic devices assist the amputees in performing their physical activities independently. The lower-limb prostheses could broadly classify as below-knee (transtibial) and above-knee (transfemoral) prosthetic devices. It can be passive, semi-active, or active type. Passive devices have constant damping characteristics, so they cannot accommodate various gait conditions in real time. Active devices are electronically controlled prosthetics with computational intelligence. It can provide different damping levels in the swing phase (foot swings in the air) of the gait cycle and also for varying walking speeds. However, active devices are expensive and also consume more energy. Semi-active devices are variable dampers that abruptly change the damping force during the gait cycle with a suitable control scheme. It can reduce power consumption and also provides user adaptability [30].

The prosthetic knee joint with MRF brake is commercialized in 2000 [31]. In this braking device, the MR fluid is subjected to shear mode to control the rotary stiffness. Hence, it provides the flexion (bending) resistance in real time by varying the magnetic field as the amputee walks. Carlson et al. [32] discuss the smart prosthetics using MR damper that enables effective semi-active gait control. They demonstrate a mono-tube MRF damper used to control the artificial limb motion in the above-knee prosthetics. The control unit receives measured knee angles and force data using sensors. It provides a time-varying current signal to the electromagnet, which induces the magnetic field and generates the damping force. The system responds quickly to sudden changes in walking dynamics.

Kim and Oh [33] developed a semi-active above-knee prosthesis using the rotary MRF damper. The torque dissipation in the MR damper is control by supplying current to the solenoid using a microprocessor. The 3 DOF leg simulator was designed with an MRF damper to analyze the walking motion. They used a repetitive controller, conjunct with a PD control law and computed control law for tracking the desired knee angle. The gait period is determined using a gyro sensor attached to the thigh. Based on the walking speed, they performed real-time tracking control by using the generated gait period. It shows good performance in the swing phase (foot swings in the air) and adapts to walking speed. This prosthetic requires further structural improvement to support the weight of the amputee in the stance phase (foot is in contact with the ground) and in the passive condition.

Herr and Wilkenfeld [30] designed MR fluid-based variable damper knee prosthesis. They compared the user-adaptive and conventional above-knee prostheses to evaluate the knee damping values. In the MR brake device, the MR fluid is subjected to shear mode to control the knee resistive torque. The clinical evaluation shows that the user-adaptive control scheme with local sensing was essential to perform biological activities more naturally with early stance knee flexion. It controls the early stance damping compared to passive devices. The user-adaptive MR knee prosthetic is energy-efficient, with a microprocessor and lithium-ion rechargeable batteries for power. Their future research focuses on improving the power supplies, effective knee actuator design, and distributed sensory architecture.

Johansson et al. [34] investigate the advantages of the variable damping knee over passive prostheses. They compared the two variable damping knees, the Ottobock C-leg (hydraulic-based) and Ossur Rheo (MR fluid-based), with the mechanically passive device (Mauch SNS hydraulic). Based on their test data, variable damping knee provides biomechanical advantage and decreased metabolic rate. The advantages of variable dampers over the passive dampers are the smooth transition of gait and decreased hip work at the terminal stance and toe-off. They showed that MR fluid-based knees possess better control in the hip swing phase behavior and prosthetic foot energy storage. Li et al. [35] developed an intelligently controlled prosthetic ankle joint prototype using a linear MR brake. During the swing phase, the dorsiflexion phase (raising the foot upward toward the shin) is introduced for the amputee, using an MR brake. Walking experiments were performed with and without brake control. For the experiment with brake control, the amplitude of knee displacement and hip angle decreased, thus protect the amputee from lifting the knee, but result in discomfort of the amputee. In the future, they aimed to reduce the weight of the prosthetic device and with suitable software to adjust the walking speed.

Jonsdottir et al. [36] analyze the design parameters of the prosthetic knee in the existing design to maximize the braking torque for supporting heavier amputees. The result indicates that an increase in core size maximizes braking torque significantly. For increasing the core size, the coil size can reduce without changing the external dimensions. But, reducing the coil size also affects the core saturation. Hence, they reported that a core size should not increase beyond 10%. Further, Gudmundsson et al. [37] framed a multi-objective optimization problem to determine the design parameters of the MR brake. The design goals are maximizing the field-induced braking torque, minimizing the knee rotary stiffness in the off-state, and minimizing the weight of the braking device. Their analysis provides optimal MR brake design values with a core size of 10.7 mm, 30–35 μm of the gap between the blades, and 71 thin blades. Ochoa-Diaz et al. [38] developed variable damping above-knee prosthesis based on the polycentric configuration with the four-bar linkage mechanism. The advantage of the polycentric knee has a variable center of rotation that provides stability for all phases of the gait cycle. They tested the prosthetic device in the passive mode by considering the situation as the battery turns off. It shows better stability and satisfactory performance in the passive mode. They concluded to focus on implementing the control strategy to use the prosthetics in the active mode.

Park et al. [39] developed an above-knee prosthetic device that operates in both semi-active and active modes. They used a flow-type MR fluid damper for the semi-active mode of operation and an electronic commutated motor for an active mode of operation. The electronic motor and MRF damper both provide high stability and tracked the preferred knee joint angle using a proportional derivative (PD) controller. They tested the device on the ground level for varying walking speed. At low-walking speed, the actual knee joint tracks the preferred knee joint angle. As the walking speed increases, the device deteriorates the tracking accuracy owing to the sluggish response of the MRF damper. Xu et al. [40] designed and fabricated a four-bar linkage lower-limb prosthetic knee with an MR damper. The damper operates in shear mode with a double-ended structure. They derived the control algorithm from driving equation based on the MRF damper experiments. The device performance tested for a constant current of 1.6 A shows the maximum bending angle with a stable gait. They observed that the maximum bending angle decreases with increasing the current. The controlled current using the control algorithm observed a delay time response of 0.035 s between the knee and the ideal reference knee angles (natural swing angle of a human knee joint). Their future work focuses on structure optimization, cutting-edge control algorithm, and gait spontaneous transitions at varying loads.

Fu et al. [41] stated that ignoring the effect of MRF damper hysteresis results in insufficient damping force and also enlarged the tracking error. They developed the two-bar linkage prosthetic knee with a double-ended MRF damper in shear mode to analyze the MRF damper hysteresis. They performed real-time simulations of the MR prosthetic device in the test platform to compare the proposed sliding mode tracking control method (SMTC) with the computed torque plus proportional derivative (CT + PD) control method. The SMTC method subdues the MR fluid damper hysteresis and controls the swing angle by providing controllable joint torque. Their simulated result shows that the SMTC error is 80% less than (CT + PD) control method, but SMTC was robust. Their prototype mimics the natural swing of the knee joint, and the swing angle produced by SMTC was 34% less than (CT + PD) control method.

Gao et al. [42] optimized the MRF damper design for the prosthesis by minimizing the total energy consumption in gait cycle and damper weight. Particle swarm optimization algorithm was used to optimize the geometric dimensions of the MR damper. The prosthetic device was designed, and the human knee kinetic characteristics were simulated using an MR damper, spring, and DC motor. They obtained energy consumption by considering the MR damper in the on and off-states. In the initial stance and swing phase, the MR damper was in the off-state; in late stance phase, it was in the on-state and works as a clutch. They investigated the optimal weight of MR damper. Their future work focuses on completing the fabrication and clinical trials. Nordin et al. [43] simulated the variable MRF damper for prosthetic knee using a fuzzy-proportional–integral–derivative adaptive controller (fuzzy-PID) for varying frequency. They simulated in MATLAB SIMULINK using the inertial parameters acquired from the OpenSim model. In the heel strike phase, the fuzzy-PID controller shows better performance than the PID controller to reduce the vibrations efficiently at varying frequencies. They tested the MRF damper in the UTM machine to show the tuning behavior of the damping force to the applied current.

Seid et al. [44] designed a dynamic system model of the single-axis knee with the damper. The performance of the dampers was evaluated for the above-knee prosthetic in the swing phase. In this model, the MRF and the hydraulic damper designed as controllers to control the swing phase damping. They determined the damper control parameters by formulating an optimization problem. The designed control parameters can employ as the control strategy of microcontroller-based prosthetic knees and as a benchmark. Their result shows that MR damper in the swing phase shows a better capability than a hydraulic damper. Further, Seid et al. [45] framed a multi-objective optimization problem by constraining the MR damper valve in the desired volume. They analyzed geometrical design variables of the MR damper by mapping the results of finite element analysis with the response surface method (RSM). The designed MRF damper shows a 71% reduction in weight than the existing one and better performance in the swing phase with optimal damping force. Then, Seid et al. [46] proposed a simple assembly design for the prosthetic knee, with three major parts, socket connector, MR damper, and shank connector. They performed finite element analysis to study the overall knee structure performance to withstand the stance phase loading condition based on ISO 10328:2006. The result shows that their proposed prosthetic knee model was more compact and lighter (68% reduction by weight and 40% reduction by volume) than the Rheo Knee. Their future work includes prototyping, damper dynamic characterization, clinical trials, and gait analysis.

Arteage et al. [47] consider MRF brake (Lord MRF-140 CG) as torque limiter for the prosthetic knee prototype to provide active movement and stability for the transfemoral amputee. The rotation speed of the prosthetic knee was affected by the MR actuator speed. High torque requires for a normal walk. So, the transmission system was designed to multiply the torque delivered by the servomotor. The torque obtained by the servomotor and by the torque limiter combines to provide the maximum braking torque. They used the closed-loop proportional–integral (PI) controller scheme to control the desired position of the actuators. The prototype shows a satisfactory result as compared with the reference graph of the human walk. Arteaga et al. [48] developed a robotic ankle and foot prosthesis prototype using MR fluids for greater adaptability. This design comprises an MRF actuator to absorb shocks during walking and an electric actuator to control the ankle movement (dorsiflexion and plantar flexion). The prototype shows the capability to mimic the angle and torsion patterns of the human ankle.

This section discussed the growth of MR technology for lower-limb prosthetic devices. Several research works based on design optimization help to reduce the weight of the device and also improve the device performance. Most of the developed prototypes are in progress to check the consistency of the device based on the clinical trials.

Conclusion

This article briefly reviewed the MRF properties based on their constituents and various sedimentation techniques for real-time applications. Further, this article highlights the MR fluid damper in lower extremity prostheses based on device design, mechanism, control algorithm, and bio-mechanics capability. In addition to regular walking, amputee often confronts irregular terrains, sudden impact, and heavy work, which need variable damping to resemble a normal gait cycle. Depending upon the mode of application, MR fluid damper can serve as a clutch or brake to offer user-centric adaptability that helps in saving metabolic energy. Currently, MR-based prosthetics devices use local sensing for actuation. In the future, MR-based devices can be coupled with newer technologies like bionic limbs to obtain signals from an individual's muscles for better functioning. Due to faster response, good controllability, and flexibility to operate in different modes, MR fluid serves as a promising material for developing prosthetic devices in the present and future.

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