CHAPTER 4 RESULTS AND DISCUSSION

The designed characteristics of nanorobots, control algorithm, and circulatory system parameters and blood model are defined in chapter 3. In this chapter, nanorobots are simulated to repair the injured area in rigid blood vessel with non-Newtonian blood flow for examining the efficiency of PSO as a control algorithm. The nanorobots task is to travel along the rigid blood vessel in order to seek for the wound and, then, assemble together for covering the wound. The wound coverage rate is the indicator for how much they could repair the wound. The speed of nanorobots to accomplish the repairing task is indicated by the number of iterations of nanorobots in the simulation. Another aim is to investigate the effect of different settings of nanorobot characteristics including the perception range, maximum velocity, and response speed to the nanorobot performance. The perception range is the area that nanorobots can perceive the environment, which is dependent on how far the sensors can sense. The maximum velocity is the highest velocity that nanorobots can travel inside the blood vessel. This ability depends on the power of the actuators. The response speed shows how fast nanorobots could react with the environment and moving. This depends on the speed of computing unit installed in the nanorobots. The characteristic of early stage nanorobots should be simplest as they could perform effectively in order to reduce the complexity of nanoparts.

4.1 System Setting

To investigate the performance of canonical PSO-based nanorobot control in non-Newtonian blood flow, the experiments are conducted with the following parameter setting. Nanorobots operate in the non-Newtonian blood flow in an arteriole, which is simulated by a rigid cylindrical tube of 30 μm in diameter and 500 μm in length as illustrated in Figure 4.1. Figure 4.2 shows the coordination for blood vessel in the simulation, the coordination for radius ranges from -15 to 15 and for length ranges from -250 to 250. Two ends of the tube are connected as a torus. The wound is simulated as a cylinder shape with 5 μm radius and 3 μm in length as showed in Figure 4.3. The position is fixed at (15, 270°, 0) in cylindrical coordinates (r, θ, z). The Figure 4.4 shows the positon of wound in the vessel in ratio. The nanorobots simulate activated platelets, which are 2 μm in diameter and spheroid in shape. Comparing with the wound volume, the 29 nanorobots are required to fill in the most of the wound. However, there are some empty spaces because of the shape of the nanorobots. The size of nanorobot is compared with vessel size and wound size in the ratio in Figure 4.5
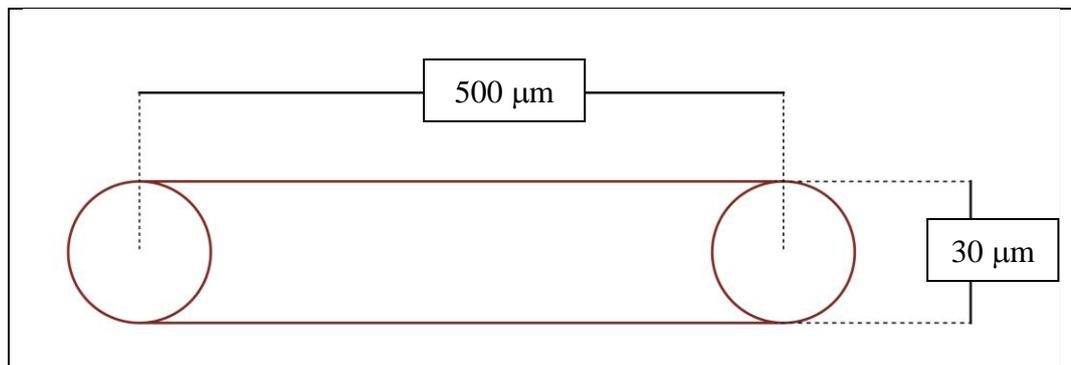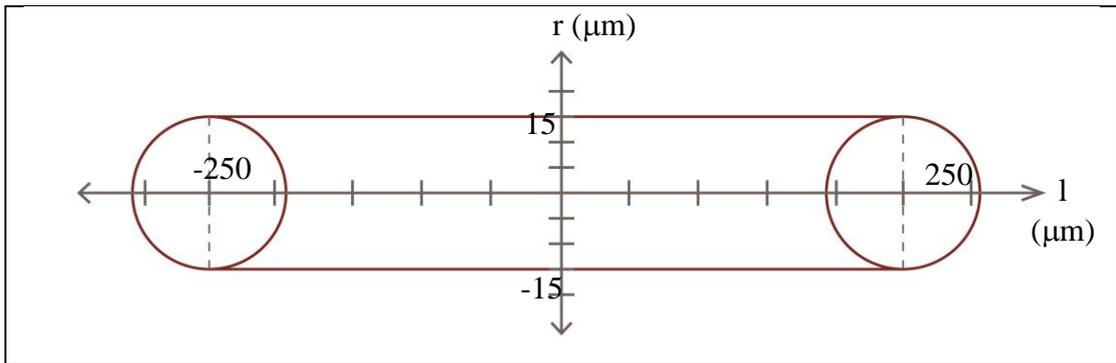

Figure 4.1 The dimension of blood vessel.

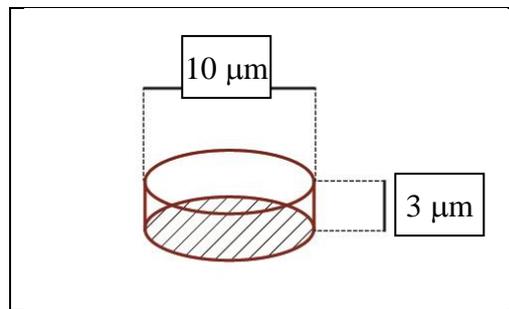**Figure 4.2** The coordination for blood vessel.

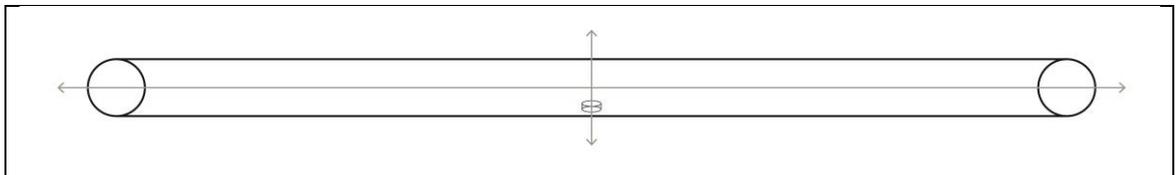**Figure 4.3** The dimension of the wound in this simulation.

Figure 4.4 The illustration of the blood vessel and the wound in this simulation.
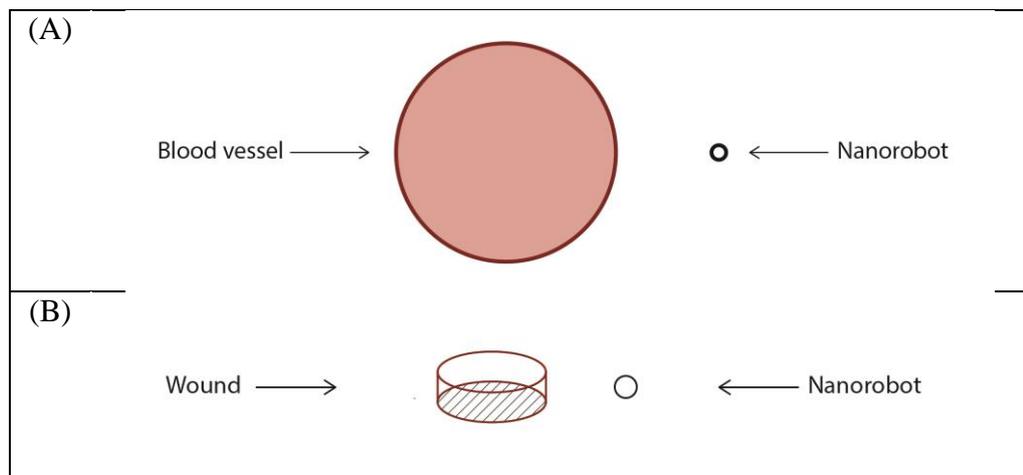

Figure 4.5 (A) The comparison between the size of a nanorobot and the blood vessel in ratio and (B) The comparison between the size of a nanorobot and the wound in ratio.

For H-B model, there are some constant parameters including the power law number, *n*, which is set as 0.5, and the yield stress,τ_y , which is 0.001 Pa [16]. The shear stress at wall,τ_w, can be computed from equation (3.13) with pressure gradient, $-\frac{dP}{dx} = 20400$, and *m* = 0.0019 by computing equation (3.11). Within the simulated vessel, the number of nanorobots is fixed at 142 as it corresponds to the platelet concentration in normal people with 40% hematocrit. The initial positions of nanorobots are randomly set within the blood vessel lumen. For the PSO control algorithm, the constriction coefficient is fixed at 0.729 as recommended in [43].

According to the purpose of this study, the experiments are divided into 2 parts:
- The experiments for investigating the effect of the different setting of nanorobot characteristics.
- The experiments for investigating the performance of the nanorobot control algorithms.

In this study, the effect of different nanorobot capabilities including the perception range (*PRange*), the maximum velocity (*VMax*) and the nanorobot response speed (*NRTime*) are of interest. The *PRange* represents the nanorobot perception ability. The *VMax* is the maximum velocity of nanorobots. The *NRTime* determines how fast the nanorobots can acknowledge to the change in the environment and respond accordingly. Three groups of experimental settings are used for investigating the effect of each parameter. Each parameter is set as the ratio of the relative attribute. The *PRange* value is set as the proportional of the blood vessel radius. The *VMax* value is the ratio of the blood velocity. Except the *NRTime*, it is set as the unit of iteration of the simulation. The ratio setting is used because it is easy to adapt when the environment is changed.

In each experiment, the main investigated parameters are varies while the others are fixed as follows:
- The effect of different perception range: *PRange* is set at 1/8, 1/4, 1/2, 1 and 2 times of the blood vessel radius which the actual setting values are 1.875, 3.75, 7.5, 15, and 30 µm. *VMax* and *NRTime* are fixed at 15 mm/s and 0.01 s respectively.
- The effect of different the maximum velocity: *VMax* is set at 1/8, 1/4, 1/2, 1 and 2 times of the maximum blood velocity which the actual setting values are 3.75, 7.5, 15, 30, and 60 mm/s. *PRange* and *NRTime* are fixed at 7.5 µm and 0.01 s.
- The effect of different the nanorobot response time: *NRTime* is set at 0.01, 0.002, and 0.001 s. *PRange* and *VMax* are fixed at 7.5 µm and 15 mm/s.

In order to investigate the performance of PSO control mechanism, the nanorobots with random movement are used for comparing with the PSO-based nanorobots. All algorithms will be applied to all experiments above. There are three algorithms including: random movement, PSO1 and PSO2.

For the random movement, the nanorobots are randomly selected the new positions and move to that position without consideration. Note that when the random movement nanorobots found the attraction signal, they are also influenced with the same way as it is influenced the PSO-based nanorobot. It implies that the random process of nanorobot is only applied for the movement behavior. Other processes which related to the self-assemble process such as the attraction signal sensing, generating the attraction signal or wound adhering are in the same control mechanism as the PSO-based nanorobots.

For PSO algorithm, there are divided into two types of parameter setting: PSO1 and PSO2. The PSO parameters that were set differently are c_1 and c_2. These parameters are used as the confidence of the own knowledge and social knowledge respectively. By the values of c_1 and c_2 are computed from equation (3.4). PSO1 represents PSO that sets the values of c_1 and c_2 equally at 2.05 for giving confidence in nanorobot own knowledge as much as social knowledge in all situations.

In PSO2, the parameter setting are changed in between the searching process in order to balance the influence from nanorobot own knowledge and social knowledge. Values of c_1 and c_2 depend on the situation which could be defined by the state of nanorobots. The different states of nanorobots are determined from the situation in the neighborhood as illustrated in Figure 4.6. At the state0, Nanorobots have no neighbor around their perception range. In this state, nanorobots should confide to their own experiences. The reason is the social knowledge is out of date because there is no neighbor to update the social knowledge. Moreover, increasing the confident of personal knowledge could increase the exploration because each nanorobot could search scatteringly. At the state1, some neighbors are found but no attraction signals. In this state, the social knowledge is maintained by the neighbors around. The confident of the social knowledge could be increased. However, there is no attraction signal; either neighbors or nanorobot itself has the equal chance to discover the wound. Thus, both own knowledge and social knowledge should have equal confident. Nanorobots are defined as state2 when nanorobots found the attraction signal or the optimal nanorobot. For this state, nanorobots should follow the optimal nanorobots in order to go to the wound. Thus, the c_2 is set higher than c_1. It implies to give higher confident to the optimal nanorobots. According to the explanation above, the values of c_1 and c_2 are set as follows:
- When nanorobot is in state 0, the values of c_1 and c_2 are set at 2.733 and 1.367.
- When nanorobot is in state 1, the values of c_1 and c_2 are set at 2.05 and 2.05.
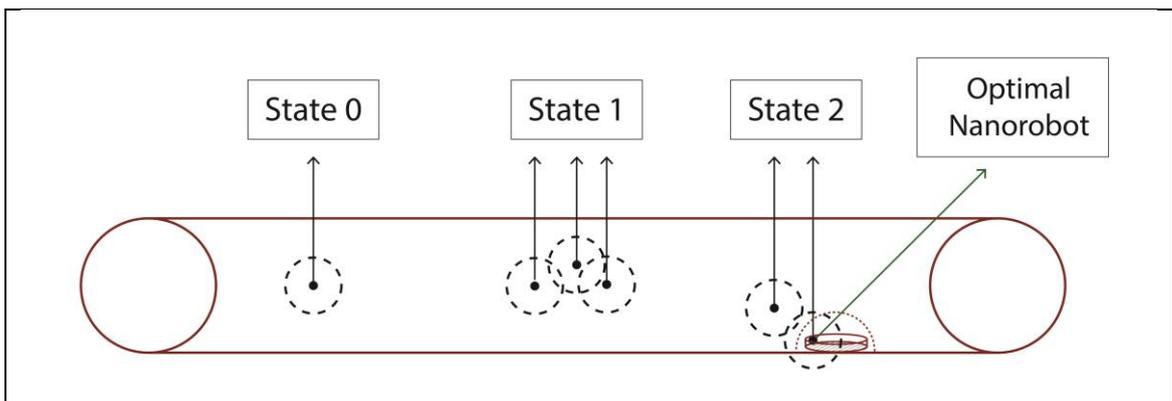- When nanorobot is in state 2, the values of c_1 and c_2 are set at 1.025 and 3.075.

Figure 4.6 The nanorobots in different state.

Each experiment is replicated 40 times to examine the reliability of the result. The ratio of nanorobots that can reach the wound, or wound coverage rate, and the number of iterations are the indicators of nanorobot performance. The higher the wound coverage rate indicates the better the performance. In term of the number of iterations, the smaller number indicates the better result as it reflects the speed for completing the task.

4.2 Experimental Results

4.2.1 The Effect of Varying Perception Range
The experimental investigation results for the case of varying the perception range of nanorobots are shown in Figure 4.7. In term of accuracy, nanorobots performed effectively with all perception range. At the higher perception range, nanorobots obtain slightly higher wound coverage rate. This is reasonable because the higher the perception range gives the greater chance for nanorobots to meet and get information from neighboring nanorobots as well as from the environment. A low-valued perception range nanorobots would move pass the wound even though it gets near the wound as it is not near enough to sense the wound in its perception range. Comparing between different algorithms, all algorithms can achieve the goal. However, when the perception range is greater than a half of the blood vessel radius, the PSO-based nanorobots performed better. The reason is the PSO-based nanorobots used the advantage of wider perception range to obtain more data from the neighbors. On the other hand, the wider perception range did not affect the nanorobot with random movement behavior. Thus, the accuracy of nanorobot with random movement did not improve.

In term of speed to achieve the goal, nanorobots achieved the goal within 10,000 iterations with all perception range. It cannot be clearly concluded the effect of the perception range to the speed. From the graph, the speed seems to increase when the perception range increases. Nevertheless, the speed started decrease after the perception range increases to 1/2 of blood vessel radius. It may be because the perception area is too large; nanorobot can be led by bad influence.
Comparing between different algorithms, the PSO-based nanorobots perform better than the random movement and the PSO2 obtains the higher speed than the PSO1. For varying perception range does not highly affect the nanorobots with random movement because they generate their random movement without interacting with other nanorobots or the environment.
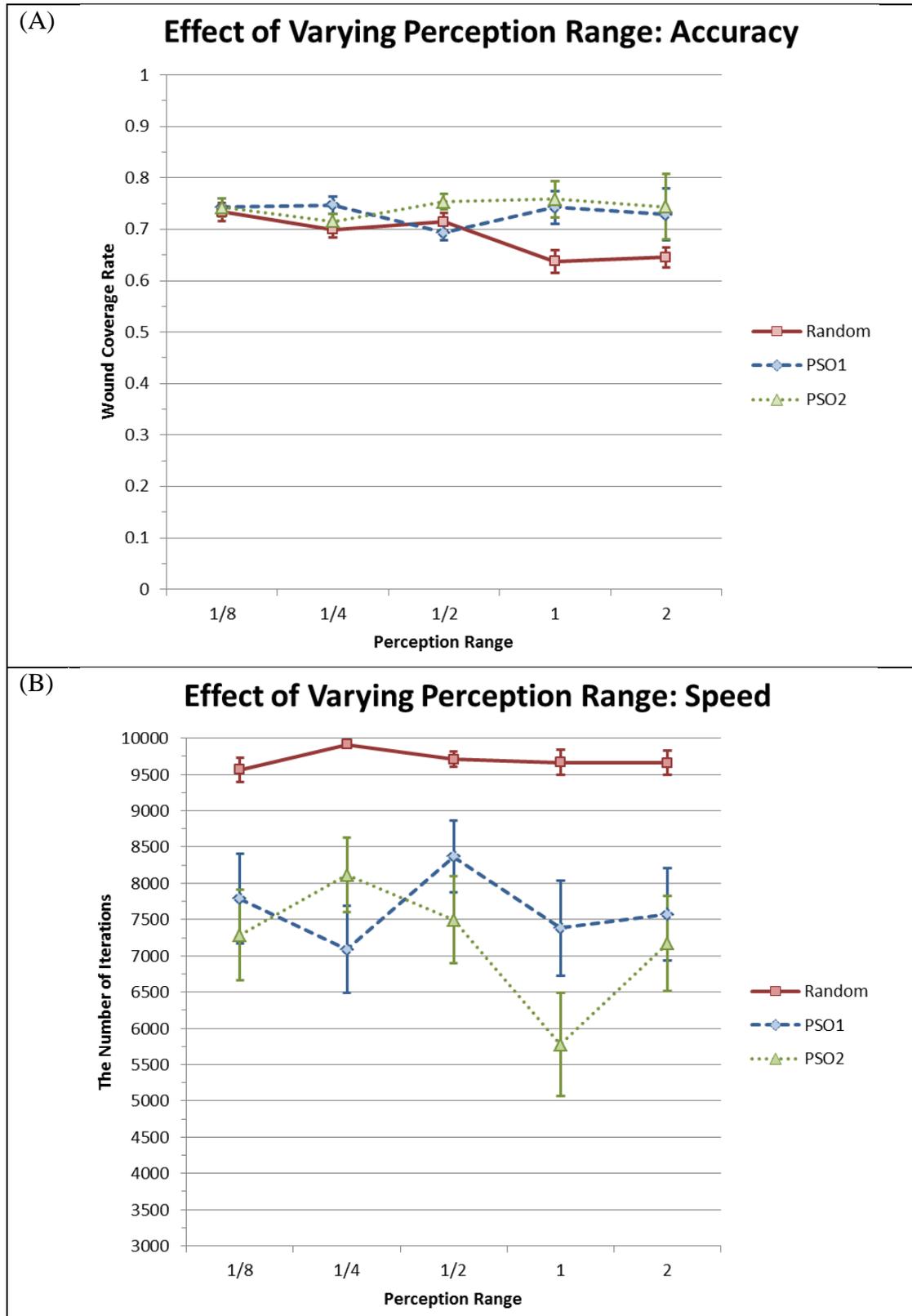
(A)

Effect of Varying Perception Range: Accuracy

(B)

Effect of Varying Perception Range: Speed

Figure 4.7 The comparison of experimental results between random movement, PSO1 and PSO2 in non-Newtonian model for the variation of *PRange*: (A) the median wound coverage rate and (B) the mean number of iterations.

4.2.2 The Effect of Varying Maximum Velocity

In the case where the maximum velocity of nanorobot is varied, the results are illustrated in Figure 4.8. In term of accuracy, nanorobots cannot accomplish the task when the maximum velocity is set at 1/8 of blood velocity. The graph showed that the wound coverage rate is lower than 0.1. However, with higher maximum velocity, nanorobots achieved higher wound coverage rate. The reason is because the greater maximum velocity allows nanorobots to move more freely against the influence of blood flow. When the maximum velocity of nanorobots is too low, nanorobots are incapability to complete their task because they cannot move against the blood flow. The results show that the maximum velocity should be set as high as it can be. However, this study aims to define the early-stage nanorobot characteristics, which are concerned with the simplification of nanorobots. For high maximum velocity, the drive-part needs complex technology, which can conflict with the purpose of early-stage nanorobots.

In term of speed to achieve the goal, the result conforms to the result of accuracy. The nanorobots could not achieve the goal within 10,000 iterations when the maximum velocity is set at 1/8 of blood velocity. When the maximum velocity is set higher than 1/8 of blood velocity, the speed to achieve the goal of nanorobots is also increases as well.

Comparing between different algorithms, the PSO-based nanorobots perform better than the random movement and the PSO2 obtains the higher speed than the PSO1. However, when the maximum velocity is set at 1/8 of blood velocity, the random movement could perform slightly better than the PSO-based nanorobots. The reason is when the nanorobots passed though the wound, the PSO-based nanorobots will try to move back to the wound but it cannot move against the blood velocity because of the low maximum velocity. Thus, many iterations are wasted. On the other hand, the random movement nanorobot will randomly move forward without trying to go back.
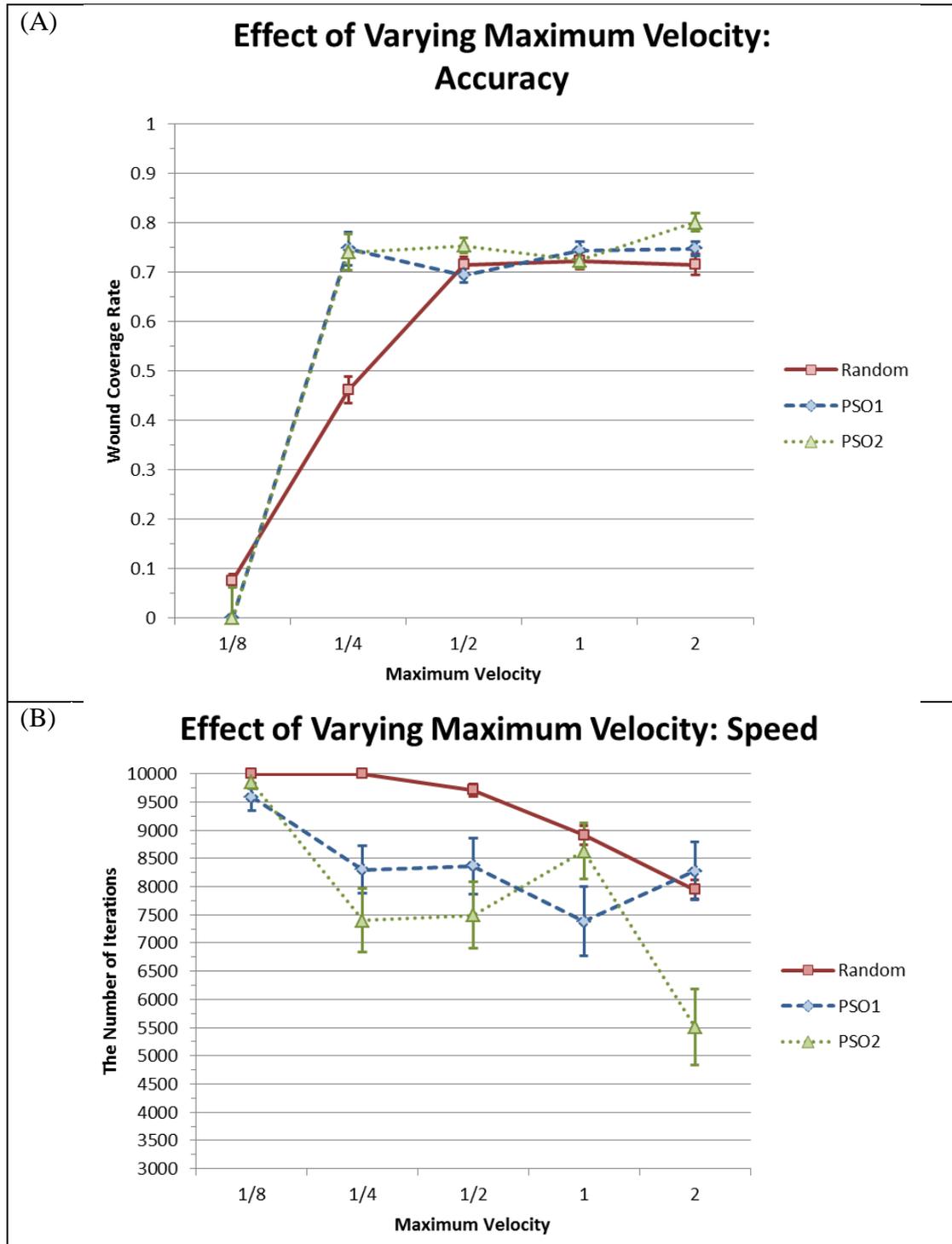
(A)

(B)

Figure 4.8 The comparison of experimental results between random movement, PSO1 and PSO2 in non-Newtonian model for the variation of *VMax*: (A) the median wound coverage rate and (B) the mean number of iterations.

4.2.3 The Effect of Varying Response Speed

The nanorobot response speed denotes how fast the nanorobots could response to the situation; the smaller value should provide the better performance. The results of varying nanorobot response speed are presented in Figure 4.9. In term of accuracy, nanorobots performed effectively at all response speed. In case of speed to achieve the goal, nanorobot at all response speed could fill the wound within 10,000 iterations. Nevertheless, the result cannot conclude the best setting of the response speed. From the pre-experiment process, when the iteration is higher than 10,000 iterations, the wound coverage rate did not improve much. The wound coverage rate was only changing around the current value. This can be happen because the method for calculating the wound coverage rate has some stochastic part which the testing points are randomly selected from the wound area. In addition, there are some empty spaces left even when the wound is fully covered with nanorobot because of the shape of nanorobots. Hence, the wound coverage rate might be varying even with the same number of nanorobots. Another reason is the space that was left behind was too small for the nanorobot but it was big enough to effect the wound coverage rate. Thus, the wound coverage rate might not reach the 0.8 condition even when the wound is almost covered. According to these reasons, the averages of the number of iteration are plotted in the case when the nanorobot could fill the wound within 10,000 iterations as presented in Figure 4.10. It shows that the faster nanorobot response speed is the faster nanorobot could achieve the goal. Moreover, the numbers of iterations from PSO algorithms are lower than 4,000 iterations. With the slowest response speed, 0.01s, the number of iteration is 37% faster than the random movement nanorobot.
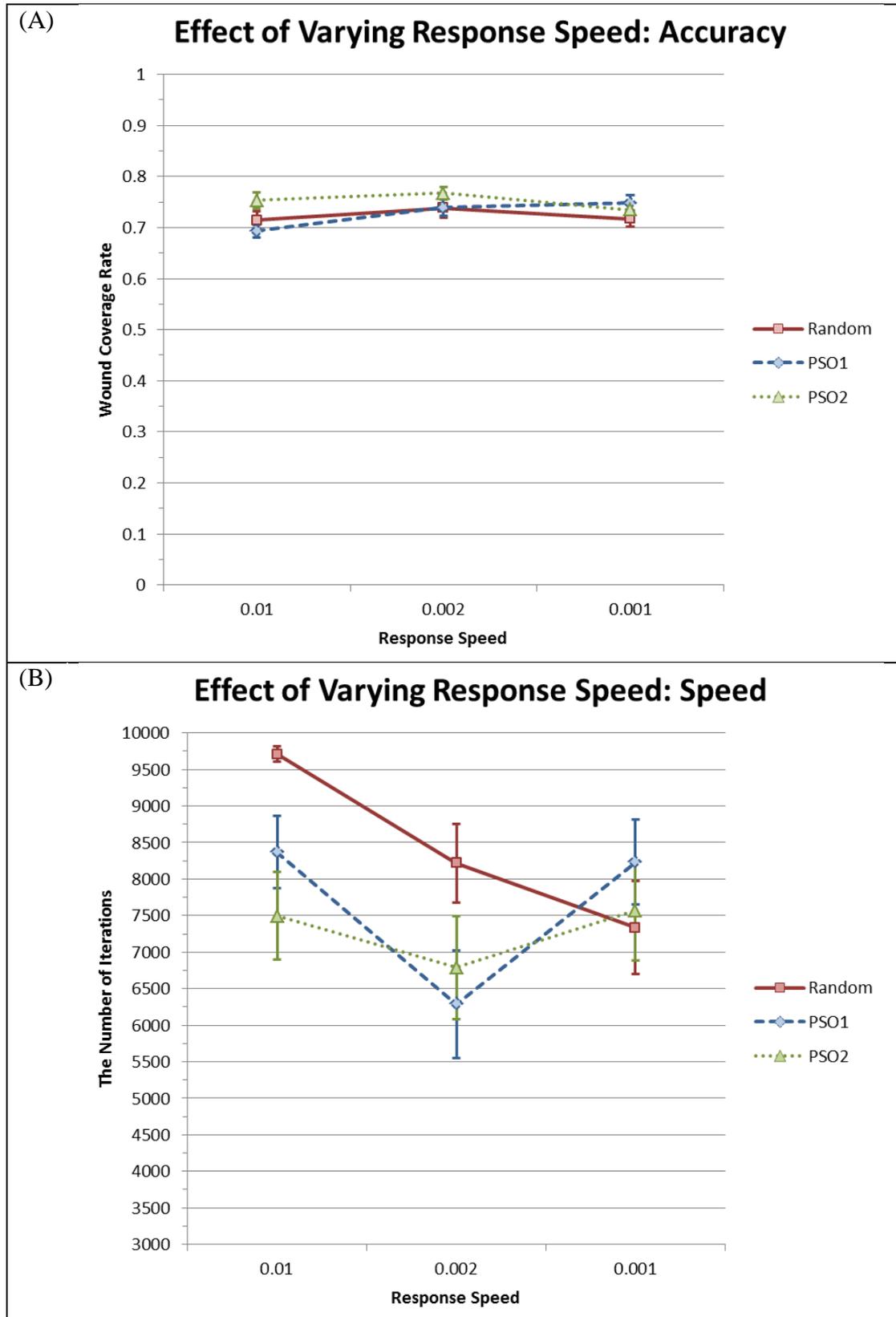
(A)

(B)

Figure 4.9 The comparison of experimental results between random movement, PSO1 and PSO2 in non-Newtonian model for the variation of *NRTime*: (A) the median wound coverage rate and (B) the mean number of iterations.
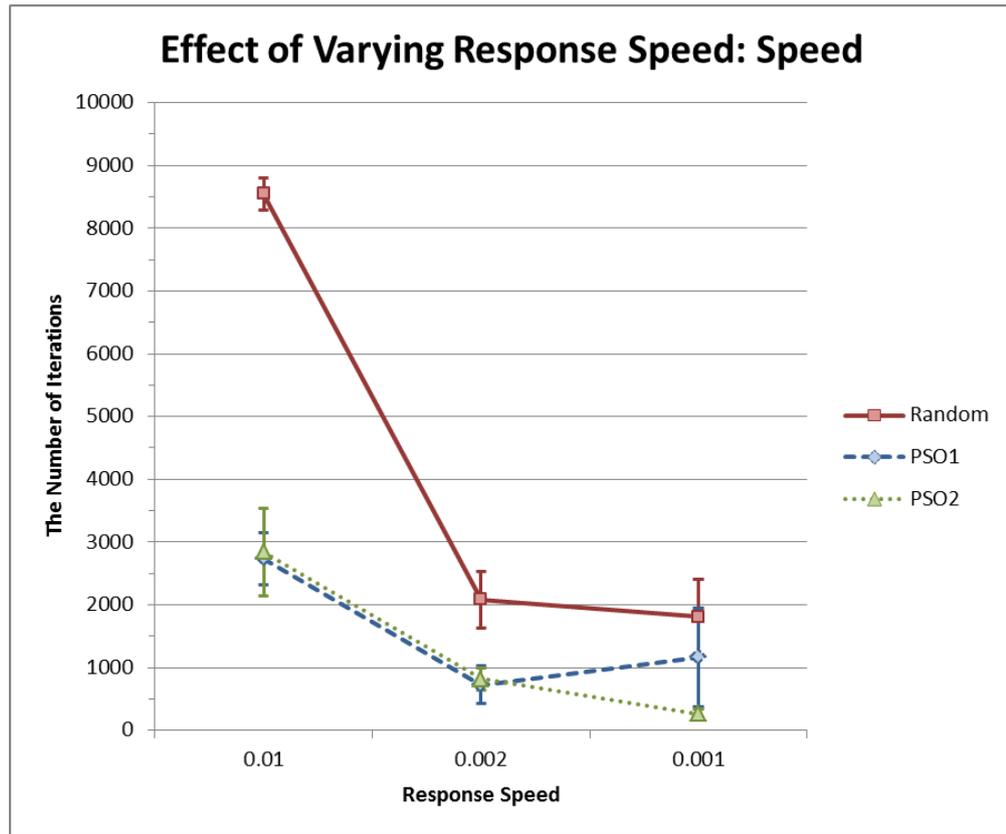
Figure 4.10 The comparison of the mean number of iterations between random movement, PSO1 and PSO2 in non-Newtonian model for the variation of *NRTime* only when the wound coverage rate reaches 0.8 before 10,000 iterations.

4.2.4 The Performance of Control Mechanism

The result of the difference control mechanisms are illustrated in Figure 4.11. All algorithms achieve similar result in term of the accuracy. The PSO-based nanorobots obtain a greater wound coverage rate than the nanorobots with random movement. This implies that PSO-based nanorobots perform more accurate. PSO2 performs slightly better as the median wound coverage rate is a little higher than that of PSO1. This shows that the PSO parameters should be adapted according to the current situation of nanorobots.

In term of speed to achieve to goal, the PSO-based nanorobot performed faster than the random movement. PSO1-based nanorobots achieve the goal 14% faster than the random movement. Moreover, the PSO2-based nanorobots achieve the goal 19% faster than the random movement.
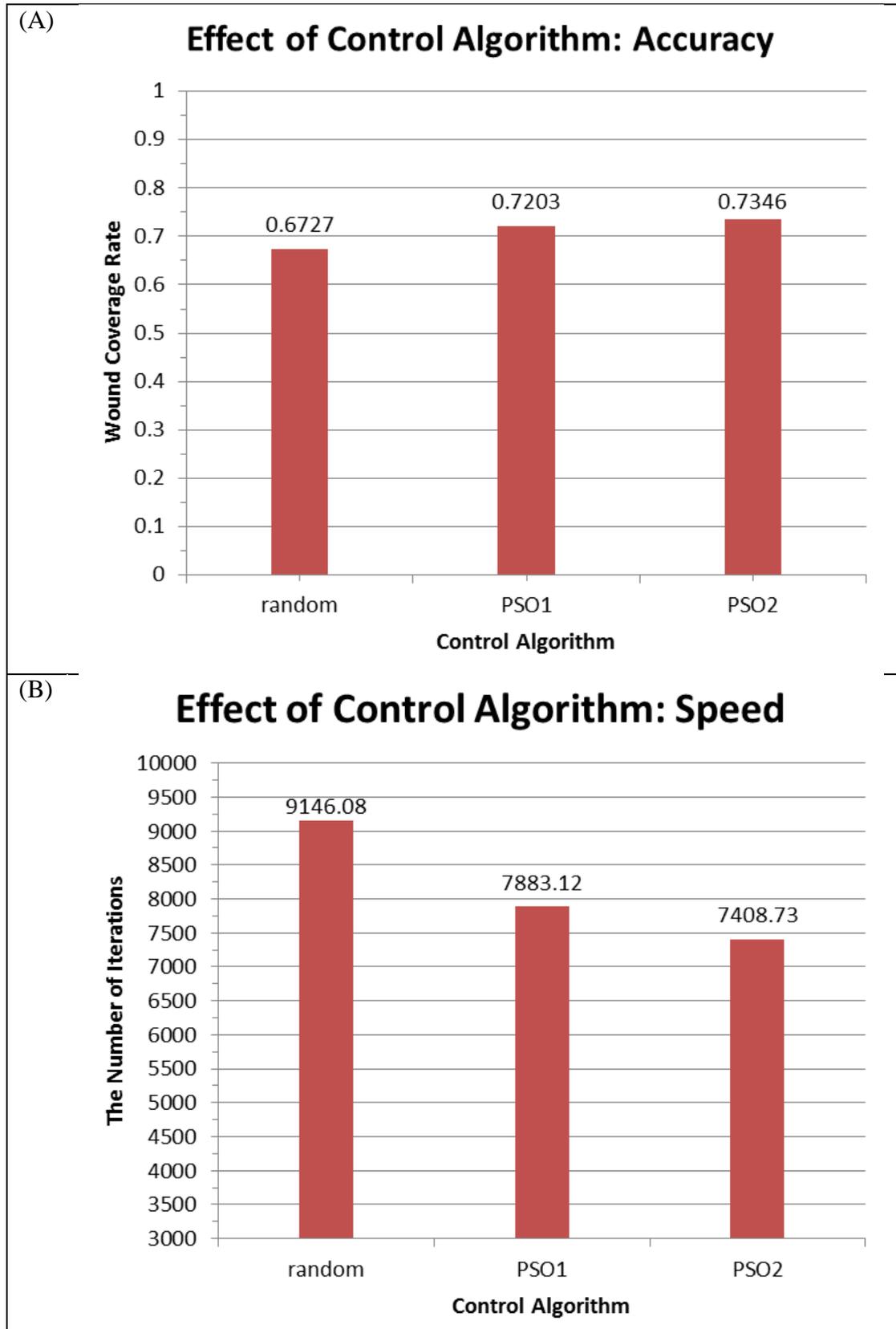
(A)

Effect of Control Algorithm: Accuracy

(B)

Effect of Control Algorithm: Speed

Figure 4.11 The comparison of experimental results between random movement, PSO1 and PSO2 in non-Newtonian: (A) the median wound coverage rate and (B) the mean number of iterations.

4.2.5 The Performance of PSO Control Algorithm in Newtonian and Non-Newtonian Blood Model

The result of the comparison of PSO-based nanorobots in Newtonian flow model in [11] and PSO-based nanorobots in non-Newtonian flow model are illustrated in Figure 4.12. The result will be compare only in term of accuracy. The speed of the algorithm could not be compared because of the different setting of maximum iteration of nanorobots. When compared the result from PSO-based nanorobots in Newtonian flow model in [11], PSO1 performed worse than the canonical PSO-based nanorobots in the Newtonian bloodstream. At low maximum velocity, nanorobots can hardly accomplish the goal due to the high velocity range at the middle of bloodstream, which is the behavior of non-Newtonian fluid. However, comparing with PSO2 based nanorobot, the PSO2 based nanorobots achieved the better result than PSO1 and more proximate results compare to the canonical PSO-based nanorobots. It may be due to the adjusted value of acceleration constants according to the current state of nanorobot.

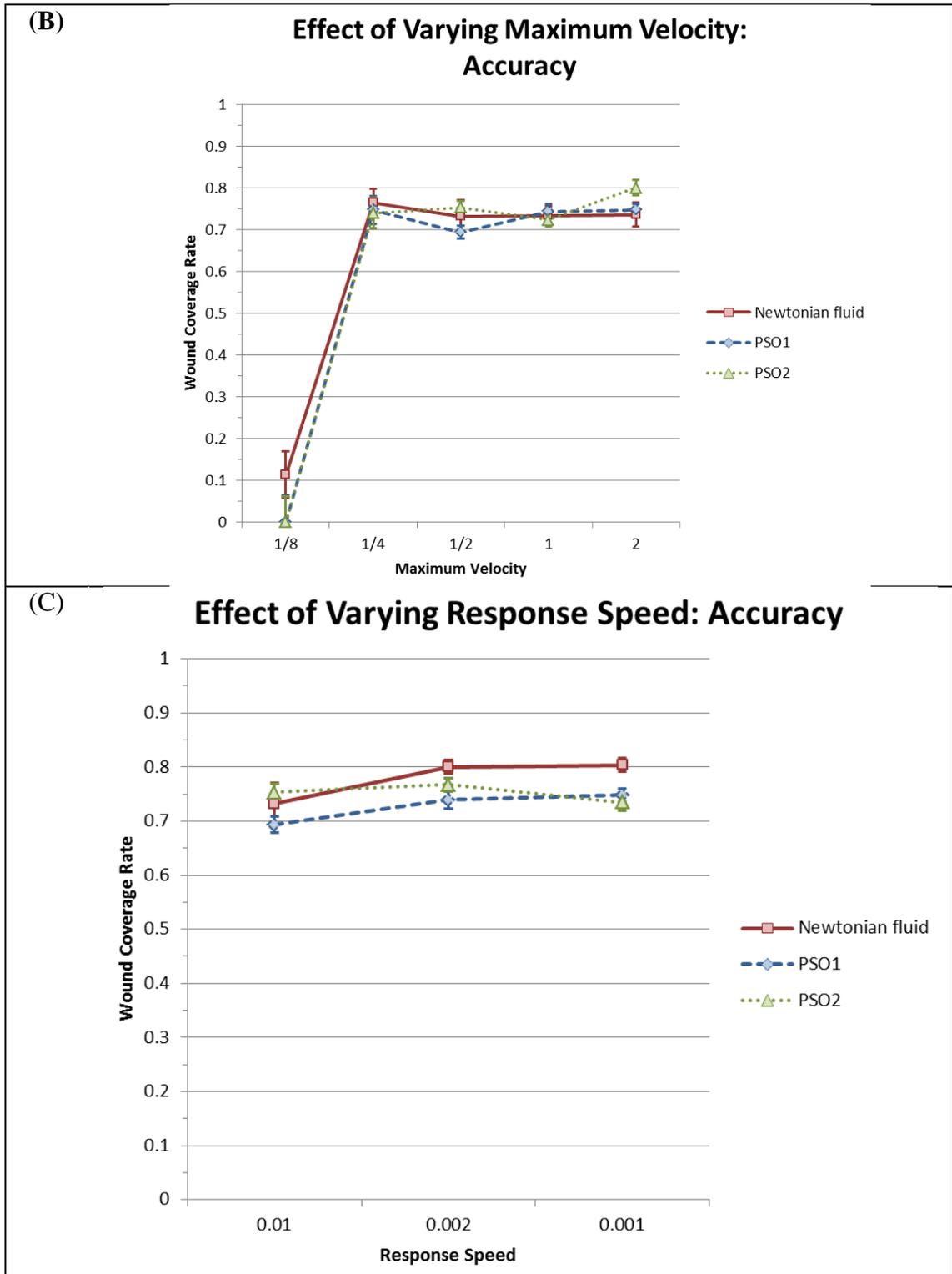All of the results are included in Table A.1-A.18 in Appendix A.
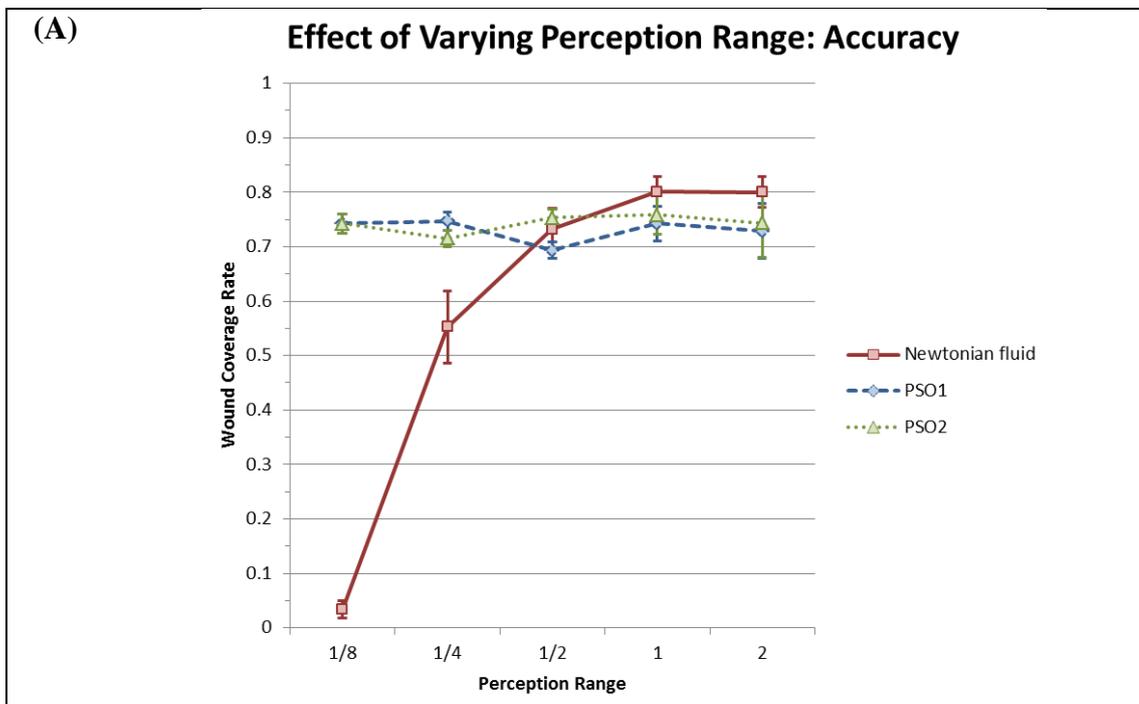
Figure 4.12 The comparison of experimental results between PSO-based nanorobots in Newtonian model and PSO-based nanorobots in non-Newtonian model: (A) effect of varying perception range, (B) effect of varying maximum velocity and (C) effect of varying response speed.