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Contemporary Drug-Eluting Stents and Functional Recovery After Percutaneous Coronary Intervention: Implications for Exercise Capacity and Cardiac Rehabilitation

Justyna Czechowicz

Stefan Żeromski Specjalista Hospital in Krakow

Osiedle na Skarpie 66; 31-913 Kraków

ORCID: 0009-0003-1035-1648

justyna.barycz12@gmail.com

Paweł Czechowicz
University Hospital in Krakow
Marii Orwid 11; 30-688 Kraków
ORCID: 0009-0008-0143-0404
pawel.czechowicz2000@gmail.com

Mikołaj Antkiewicz
Ludwik Rydygier Specialist Hospital in Krakow sp. z o.o.
Osiedle Złotej Jesieni 1, 31-820 Kraków
ORCID: 0009-0000-8735-9339
miki.antek2000@gmail.com

Aleksandra Arczyńska-Antkiewicz
Jagiellonian University Collegium Medicum
Świętej Anny 12, 31-008 Kraków
ORCID: 0009-0008-0410-4751
aaarczynska@gmail.com

Maria Drozd
Ludwik Rydygier Specialist Hospital in Krakow sp. z o.o.
Osiedle Złotej Jesieni 1, 31-820 Kraków
ORCID: 0009-0001-4246-4095
mariadrozd22@gmail.com

Zuzanna Kruczek
SP ZOZ MSWiA in Rzeszów
Krakowska 16, 35-111 Rzeszów
ORCID: 0009-0008-6153-1995
zuzanna.kruczek@op.pl

Julia Kociuba
LUX MED Sp. z o.o.
Szturmowa 2, 02-678 Warszawa
0009-0001-9030-0108
julia.kociuba@wp.pl

Dorota Kołkowicz
Provincial Specialist Hospital in Wrocław
Henryka Michała Kamieńskiego 73A, 51-124 Wrocław
ORCID: 0009-0001-3410-4401
dorotakolkowicz@gmail.com

Natalia Pawełczak
Health Care Facility of the Ministry of Interior and Administration in Lublin
Granadierów 3, 20-331 Lublin
ORCID: 0000-0001-9933-258X
n.pawelczak@student.uw.edu.pl

Agata Krawczyk
University Clinical Hospital No. 4 in Lublin
Doktora Kazimierza Jaczewskiego 8, 20-954 Lublin
ORCID: 0009-0004-8883-3572
agata.krawczyk0137@gmail.com

Martyna Kudła
University Clinical Hospital No. 4 in Lublin
Doktora Kazimierza Jaczewskiego 8, 20-954 Lublin
ORCID: 0009-0007-7465-5199
mkudla20@gmail.com

Paulina Łobaza
Medical Center in Łańcut Sp z o.o.
Ignacego Paderewskiego 5, 37-100 Łańcut
ORCID: 0009-0003-3566-005X
paulina.lobaza@gmail.com

Corresponding author: Justyna Czechowicz, justyna.barycz12@gmail.com

ABSTRACT

Background. Technological advances in contemporary drug-eluting stents (DES) have significantly improved the safety and effectiveness of percutaneous coronary intervention (PCI). However, most studies focus on traditional clinical endpoints, while the impact of modern PCI technologies on functional recovery and return to physical activity remains less well defined.

Aim. This review aimed to examine the relationship between contemporary PCI, vascular healing, and restoration of exercise capacity, with particular emphasis on cardiac rehabilitation.

Material and methods. A narrative review of current literature was performed, focusing on vascular healing after PCI, endothelial recovery with newer-generation DES, thrombotic and bleeding risks during exercise, and the role of exercise-based cardiac rehabilitation.

Results. Modern DES characterized by thinner struts and improved biocompatibility are associated with enhanced vascular healing and lower rates of late stent thrombosis. These features may support safer return to physical activity. However, exercise capacity depends not only on coronary patency but also on microvascular function, peripheral conditioning, and participation in rehabilitation programs. Cardiac rehabilitation plays a key role in improving fitness, quality of life, and long-term physical activity.

Conclusions. Contemporary PCI provides a stable basis for safe rehabilitation and physical activity. Optimal recovery requires integration of interventional treatment with structured exercise programs and individualized management. Future studies should include standardized functional outcomes.

Keywords: Percutaneous coronary intervention (PCI), drug-eluting stents (DES), cardiac rehabilitation, exercise capacity, physical activity, coronary artery disease, vascular healing, dual antiplatelet therapy (DAPT), exercise tolerance, secondary prevention

1. Intoduction

1.1. Coronary Artery Disease and PCI as a Challenge of Contemporary Cardiology

Coronary artery disease (CAD) remains one of the most important challenges for contemporary cardiovascular medicine. Despite substantial progress in prevention, diagnosis, and treatment, CAD continues to represent the leading cause of mortality worldwide and a major contributor to global disability and healthcare utilization. The global burden of CAD is driven by population aging, the persistence of major cardiovascular risk factors such as diabetes, hypertension, and obesity, and improved survival after acute coronary events, which increases the number of patients living with chronic coronary syndromes. Consequently, modern cardiology increasingly emphasizes not only the reduction of mortality and major cardiovascular events but also the improvement of long-term functional outcomes and quality of life among patients with established coronary disease (Roth et al., 2020).

Among available therapeutic strategies, percutaneous coronary intervention (PCI) has become one of the most widely used methods of coronary revascularization. Over the past three decades, major advances in interventional cardiology—including improvements in catheter-based techniques, intravascular imaging, and particularly the development of contemporary drug-eluting stent (DES) technology—have significantly enhanced the safety and effectiveness of PCI. The introduction of newer-generation DES characterized by thinner struts, improved polymer biocompatibility, and optimized drug-release kinetics has contributed to substantial reductions in restenosis and stent thrombosis, enabling PCI to be safely applied in increasingly complex patient populations and clinical scenarios (Byrne et al., 2015).

As survival after coronary interventions improves, the clinical focus has gradually shifted from solely preventing adverse cardiovascular events toward optimizing post-procedural recovery and long-term patient well-being. Functional outcomes—such as exercise capacity, physical activity levels, and patient-reported quality of life—are increasingly recognized as essential components of comprehensive cardiovascular care. Participation in structured cardiac rehabilitation programs and the restoration of physical activity are therefore considered key elements of secondary prevention strategies for patients with coronary artery disease (Anderson et al., 2016).

In this context, recovery after PCI extends beyond procedural success to include the restoration of physical function and the safe return to daily activities and structured exercise. Understanding how technological advances in modern DES platforms may influence functional recovery and participation in physical activity therefore represents an important and emerging area of research within contemporary interventional cardiology.

1.2 Evolution of Drug-Eluting Stents and Their Clinical Implications

First-generation drug-eluting stents significantly reduced restenosis compared with bare-metal stents but were associated with delayed endothelialization and an increased risk of late stent thrombosis. Contemporary DES platforms were developed to address these limitations through several technological innovations. New-generation devices incorporate thinner metallic struts, which reduce arterial wall injury and flow disturbance, as well as more biocompatible or biodegradable polymer coatings designed to limit chronic inflammation and promote more favorable vascular healing responses. In addition, refined drug-release kinetics in everolimus- and zotarolimus-eluting stents have improved the balance between antiproliferative efficacy and endothelial recovery (Byrne et al., 2015; Finn et al., 2007).

These design improvements translated into superior clinical safety profiles compared with first-generation DES, as demonstrated in large randomized trials (Stone et al., 2010). Improved healing characteristics of contemporary DES have subsequently enabled investigation of shorter dual antiplatelet therapy (DAPT) regimens without increasing thrombotic risk (Palmerini et al., 2015).

1.3. Research Gap and Objective of the Review

Although contemporary drug-eluting stents (DES) have substantially improved the safety profile of percutaneous coronary intervention (PCI), the majority of interventional trials continue to prioritize hard clinical endpoints such as death, myocardial infarction, target lesion revascularization, and stent thrombosis (Bangalore et al., 2012; Stone et al., 2019). While these measures are essential for evaluating procedural efficacy and long-term safety, they do not comprehensively reflect patient-centered outcomes, including functional status, symptom burden, and health-related quality of life. The importance of such measures has been emphasized in cardiovascular outcomes research, particularly through validated instruments such as the Seattle Angina Questionnaire (Spertus et al., 1995; Rumsfeld et al., 2013).

At the same time, exercise-based cardiac rehabilitation is strongly supported by evidence. It has been shown to improve functional capacity and reduce cardiovascular risk in patients with coronary artery disease (Anderson et al., 2016). However, rehabilitation guidelines and clinical trials rarely differentiate outcomes according to the type or generation of implanted stent (Balady et al., 2007; Piepoli et al., 2016). Consequently, a translational gap persists between advances in DES technology and functional recovery paradigms.

The objective of this narrative review is to examine whether and how innovations in contemporary DES platforms may indirectly influence time of return to physical activity, exercise tolerance, safety of higher-intensity exertion, and the design of cardiac rehabilitation programs following PCI.

2. Research materials and methods.

This paper was prepared as a narrative literature review The following electronic databases were searched: PubMed, Embase, Scopus, and the Cochrane Library. Publications from 1993 to 2025 were considered, corresponding to the transition toward contemporary drug-eluting stent technology and the progressive clinical adoption of second- and third-generation DES platforms. Example keywords (used alone and in combinations) included: “percutaneous coronary intervention,” “drug-eluting stent,” “thin-strut,” “exercise capacity,” “cardiac rehabilitation,” “physical activity,” “functional recovery,” and “dual antiplatelet therapy.” Boolean operators (AND/OR) were used to integrate interventional cardiology terms with rehabilitation- and exercise-related outcomes. Eligible publications included randomized controlled trials (RCTs) evaluating contemporary drug-eluting stents (DES) and strategies for dual antiplatelet therapy (DAPT) duration (Stone et al., 2010; Valgimigli et al., 2021), as well as meta-analyses comparing first- and newer-generation DES platforms (Bangalore et al., 2012; Palmerini et al., 2012). In addition, systematic reviews and clinical trials evaluating exercise-based cardiac rehabilitation in patients with coronary heart disease (CHD) were included. Only peer-reviewed articles published in English were considered for inclusion.

3. Evolution of DES and clinical outcomes

3.1. From Bare-Metal Stents to New-Generation Drug-Eluting Stents

The introduction of coronary stents represented a major advancement over balloon angioplasty by reducing acute vessel recoil and improving procedural success. However, early bare-metal stents (BMS) were associated with significant rates of in-stent restenosis, primarily driven by neointimal hyperplasia. Vascular injury during stent implantation triggers endothelial denudation, platelet activation, and inflammatory signaling, leading to smooth muscle cell proliferation and extracellular matrix deposition within the stented segment (Finn et al., 2007). Clinically, this biological response translated into restenosis rates of 20–30%, often necessitating repeat revascularization procedures (Bangalore et al., 2012).

The development of first-generation drug-eluting stents (DES) aimed to address this limitation by incorporating antiproliferative agents such as sirolimus and paclitaxel. These drugs inhibit smooth muscle cell proliferation by interfering with cell cycle progression, thereby significantly reducing neointimal growth. Randomized trials demonstrated marked reductions in target lesion revascularization compared with BMS (Stone et al., 2010). However, the durable polymer coatings used in early DES were associated with delayed endothelial healing and chronic vascular inflammation, which contributed to concerns regarding late and very late stent thrombosis (Palmerini et al., 2012). As a consequence, prolonged dual antiplatelet therapy (DAPT) became standard practice to mitigate thrombotic risk.

Contemporary second- and third-generation DES were developed to overcome these safety concerns while preserving antirestenotic efficacy. Technological refinements include thinner metallic strut platforms, typically composed of cobalt-chromium or platinum-chromium alloys, which reduce arterial wall injury and improve hemodynamic compatibility. Thinner struts are associated with reduced flow disturbance and more rapid endothelial coverage compared with earlier, thicker stainless-steel platforms (Byrne et al., 2015). In parallel, polymer technology evolved toward more biocompatible or biodegradable coatings designed to minimize chronic inflammatory responses.

In addition, improvements in drug pharmacokinetics—particularly with everolimus- and zotarolimus-eluting stents—have enabled more controlled drug release profiles that balance antiproliferative efficacy with vascular healing. These combined structural and pharmacological innovations have resulted in lower rates of restenosis and stent thrombosis compared with first-generation devices, establishing contemporary DES as the standard of care in PCI (Bangalore et al., 2012; Palmerini et al., 2012).

Importantly, enhanced safety and improved vascular healing characteristics of modern DES provide the biological and clinical foundation for reconsidering post-PCI management strategies, including duration of DAPT and timing of return to physical activity.

3.2. Thin-Strut Stents and Improved Safety Profiles

One of the most significant technological refinements in contemporary drug-eluting stents (DES) has been the reduction in strut thickness. Early-generation stainless-steel platforms were characterized by relatively thick struts, which were associated with increased vessel wall injury, altered local hemodynamics, and delayed endothelial coverage. In contrast, second- and third-generation DES utilize cobalt-chromium or platinum-chromium alloys, enabling thinner struts while maintaining radial strength and deliverability (Byrne et al., 2015).

Thinner struts are associated with improved vascular healing and reduced thrombogenicity. Experimental and pathological studies have demonstrated that reduced strut thickness minimizes flow disturbance and shear stress gradients, facilitating more rapid endothelialization and decreasing the risk of thrombus formation (Finn et al., 2007). From a biological perspective, improved endothelial coverage is critical, as delayed healing was identified as a central mechanism underlying late and very late stent thrombosis observed with first-generation DES. Clinical data support the safety advantages of contemporary thin-strut platforms. In randomized trials comparing newer-generation everolimus-eluting stents with earlier DES platforms, significant reductions in definite and probable stent thrombosis were observed (Stone et al., 2010). Large-scale network meta-analyses further confirmed that second-generation DES are associated with lower rates of stent thrombosis and target lesion revascularization compared with both bare-metal stents and first-generation DES (Palmerini et al., 2012; Bangalore et al., 2012). Importantly, these benefits were sustained during long-term follow-up, suggesting durable improvements in vascular compatibility.

More recent randomized evidence has specifically evaluated ultrathin-strut DES platforms. In the BIOFLOW V trial, an ultrathin-strut sirolimus-eluting stent demonstrated lower rates of target lesion failure compared with a thin-strut everolimus-eluting stent at 12 months, with sustained safety during longer-term follow-up (Kandzari et al., 2017). These findings support the concept that further reductions in strut thickness may translate into incremental clinical benefit without compromising antirestenotic efficacy.

Collectively, these technological and clinical advances have translated into a markedly improved safety profile of contemporary DES. Reduced thrombotic risk and enhanced endothelial healing form the biological basis for reconsidering post-PCI management strategies, particularly the duration of dual antiplatelet therapy and the timing of return to physical activity. As such, thin- and ultrathin-strut DES represent not merely engineering refinements but clinically meaningful innovations with potential implications for functional recovery.

3.3. Shortened DAPT Duration and Clinical Implications

The improved safety profile of contemporary thin- and ultrathin-strut drug-eluting stents (DES) has enabled progressive shortening of dual antiplatelet therapy (DAPT) duration. Historically, concerns regarding late and very late stent thrombosis with first-generation DES led to the recommendation of at least 12 months of DAPT following percutaneous coronary intervention (PCI). However, advances in stent design and enhanced endothelial healing have prompted reevaluation of this paradigm.

Randomized controlled trials have demonstrated that shorter DAPT regimens may be non-inferior to standard 12-month therapy in selected patient populations. In the DAPT Study, prolonged therapy beyond 12 months reduced stent thrombosis but at the cost of increased bleeding (Mauri et al., 2014), highlighting the delicate balance between ischemic and hemorrhagic risk. Subsequent trials focusing on newer-generation DES investigated abbreviated strategies. In STOPDAPT-2, a 1-month DAPT regimen followed by clopidogrel monotherapy was non-inferior to 12 months of DAPT with respect to composite cardiovascular endpoints in predominantly low-risk patients (Watanabe et al., 2019). Similarly, the SMART-CHOICE trial showed that 3 months of DAPT followed by P2Y12 inhibitor monotherapy was non-inferior to conventional 12-month DAPT in terms of major adverse cardiac and cerebrovascular events (Hahn et al., 2019).

The GLOBAL LEADERS trial evaluated 1 month of DAPT followed by ticagrelor monotherapy compared with standard DAPT. While the study did not demonstrate superiority for its experimental strategy in the primary endpoint, it showed comparable ischemic outcomes with a similar safety profile, supporting the feasibility of shortened DAPT in selected patients treated with contemporary DES (Vranckx et al., 2018).

This issue is particularly relevant in patients at high bleeding risk (HBR), in whom the net clinical benefit of prolonged DAPT may be unfavorable. The MASTER DAPT trial demonstrated that, in HBR patients treated with biodegradable-polymer DES, abbreviated DAPT (approximately 1 month) was non-inferior to standard-duration therapy for net adverse clinical events while significantly reducing major bleeding (Valgimigli et al., 2021). These findings reinforce the concept that improved device safety permits greater individualization of antiplatelet therapy.

For physically active patients, shortened DAPT may have meaningful practical implications. Prolonged dual antiplatelet therapy increases the risk of bleeding during high-intensity or contact activities and may complicate participation in competitive sports or resistance training. Although formal exercise guidelines rarely differentiate recommendations by stent platform, the evolving evidence supporting abbreviated DAPT strategies with contemporary DES suggests a safer therapeutic framework for earlier and more confident return to structured physical activity.

Thus, technological progress in DES has not only reduced thrombotic risk but also expanded the clinical flexibility of post-PCI management, with potential downstream effects on functional recovery and patient-centered rehabilitation strategies.

3.4. Contemporary PCI and Reduction of Rehospitalization

Beyond improvements in device-level safety and shortened dual antiplatelet therapy (DAPT) strategies, contemporary percutaneous coronary intervention (PCI) has translated into measurable reductions in adverse clinical events that frequently necessitate rehospitalization.

Key among these are target lesion failure (TLF) and major adverse cardiovascular events (MACE), both of which directly influence post-procedural stability and long-term functional recovery.

Target lesion failure, target-vessel myocardial infarction, and clinically indicated target lesion revascularization—serves as a sensitive marker of device performance and vascular healing. Randomized trials evaluating second- and third-generation drug-eluting stents (DES) have consistently demonstrated lower TLF rates compared with first-generation DES and bare-metal stents (Stone et al., 2010; Kandzari et al., 2017). These reductions are largely driven by decreased restenosis and stent thrombosis, reflecting improved biocompatibility and optimized strut design.

Similarly, contemporary DES platforms have been associated with lower rates of definite and probable stent thrombosis, contributing to overall reductions in MACE (Palmerini et al., 2012; Bangalore et al., 2012). Fewer ischemic complications translate into reduced need for urgent repeat revascularization and unplanned hospital admissions. In high bleeding risk populations, abbreviated DAPT strategies enabled by improved stent safety have further reduced bleeding-related hospitalizations without compromising ischemic protection (Valgimigli et al., 2021).

Importantly, reduced event rates following modern PCI contribute to greater hemodynamic stability in the early and intermediate post-procedural phases. Stabilization of coronary perfusion and decreased risk of recurrent ischemia support earlier mobilization and safer participation in structured cardiac rehabilitation programs. While most PCI trials focus on hard cardiovascular endpoints rather than functional outcomes, the observed reductions in TLF and MACE provide an indirect but clinically meaningful substrate for improved recovery trajectories.

Thus, advances in DES technology have not only optimized procedural success but have also reduced the burden of rehospitalization, creating a more stable clinical environment conducive to sustained physical activity and functional restoration.

4. Functional recovery after PCI

4.1. Early Mobilization and Return to Physical Activity

Advances in contemporary percutaneous coronary intervention (PCI), particularly the use of thin- and ultrathin-strut drug-eluting stents (DES), have contributed to improved procedural safety and greater post-procedural stability. One of the most visible clinical consequences has been the progressive shortening of hospital stay and earlier initiation of mobilization.

Historically, prolonged bed rest after PCI was common, largely due to concerns regarding access-site complications, acute vessel closure, and early stent thrombosis. Over the past two decades, hospital stays have progressively decreased, and same-day discharge has become feasible in selected low-risk patients (Rao et al., 2011; Amin et al., 2017). This evolution reflects growing confidence in procedural safety and hemodynamic stability following contemporary PCI.

Importantly, early mobilization after PCI has not been driven solely by improvements in stent technology. In parallel with device evolution, the widespread adoption of radial access has been a major contributor to accelerated recovery pathways. Randomized trials comparing radial and femoral approaches demonstrated reductions in access-site bleeding and vascular complications with radial access (Jolly et al., 2011). These improvements have facilitated earlier ambulation and have reduced the need for prolonged post-procedural bed rest. Thus, early mobilization represents the combined effect of safer stent platforms and optimized access-site strategies rather than a consequence of DES technology alone.

Nevertheless, the improved endothelialization profiles and reduced rates of early and late stent thrombosis associated with second- and third-generation DES provide the biological reassurance necessary to support early discharge protocols (Palmerini et al., 2012). Lower target lesion failure and fewer periprocedural complications translate into greater short-term clinical stability. In high bleeding risk populations, abbreviated dual antiplatelet therapy (DAPT) strategies enabled by contemporary DES have further reduced bleeding-related complications without increasing ischemic events (Valgimigli et al., 2021), reinforcing the safety of accelerated recovery models.

Although randomized trials directly comparing early versus delayed mobilization after PCI are limited, observational and registry data suggest that early ambulation following uncomplicated procedures does not increase adverse cardiovascular or vascular events. In this context, technological progress in both stent design and procedural technique has collectively reshaped early post-PCI management.

Thus, modern PCI — integrating advanced DES platforms and radial access strategies — has created a safer and more stable clinical environment that supports shorter hospitalization, earlier ambulation, and a more confident return to light physical activity in the early recovery phase.

4.2. Exercise Capacity After Contemporary PCI (VO_2max, 6MWT, METs)

Exercise capacity is a robust and independent predictor of cardiovascular and all-cause mortality in patients with coronary artery disease (CAD). Peak oxygen uptake (VO_2max or

VO_2peak), metabolic equivalents (METs), and six-minute walk test (6MWT) distance are widely used objective markers of functional status. Higher cardiorespiratory fitness has consistently been associated with improved survival, independent of traditional risk factors (Myers et al., 2002). Even modest improvements in exercise capacity—approximately 1 MET—have been linked to significant reductions in mortality risk.

Following percutaneous coronary intervention (PCI), improvements in exercise tolerance are frequently observed, particularly in patients with limiting angina prior to revascularization. Relief of ischemia enhances myocardial perfusion, reduces exertional symptoms, and permits higher workloads during exercise testing. Studies assessing functional outcomes after successful PCI have demonstrated increases in exercise duration and MET capacity, particularly when revascularization leads to complete or functionally significant ischemia resolution (Hambrecht et al., 2004).

However, revascularization alone does not fully restore cardiorespiratory fitness. Structured cardiac rehabilitation (CR) plays a central role in optimizing post-PCI functional recovery. Exercise-based CR has been shown to significantly improve VO_2peak, exercise duration, and quality of life in patients with CAD (Anderson et al., 2016). Improvements in endothelial function, skeletal muscle oxidative capacity, and autonomic balance contribute to these gains beyond the mechanical relief of coronary stenosis.

Importantly, contemporary PCI strategies characterized by lower rates of target lesion failure, reduced stent thrombosis, and shorter dual antiplatelet therapy (DAPT) regimens create a more stable clinical environment for participation in rehabilitation programs. Reduced ischemic risk and fewer bleeding complications may facilitate earlier initiation and greater adherence to structured exercise training. While most DES trials focus on major adverse cardiovascular events rather than functional endpoints, the improved safety profile of modern PCI indirectly supports more aggressive and sustained physical conditioning strategies.

The integration of contemporary revascularization techniques with exercise-based rehabilitation therefore represents a complementary model: PCI restores coronary flow and symptom control, while rehabilitation enhances systemic cardiovascular performance and long-term prognosis. Together, these components shape the trajectory of functional recovery and long-term physical activity after PCI.

4.3. Participation in Cardiac Rehabilitation Programs After Contemporary PCI

Participation in cardiac rehabilitation (CR) remains one of the most effective secondary prevention strategies after percutaneous coronary intervention (PCI). Exercise-based CR has consistently been shown to reduce cardiovascular mortality and hospital readmissions while improving exercise capacity and quality of life (Anderson et al., 2016). Despite advances in PCI technology, structured rehabilitation remains essential for achieving meaningful and sustained improvements in functional recovery.

Aerobic training constitutes the cornerstone of CR programs. Moderate-to-high intensity continuous training improves VO_2peak, endothelial function, and myocardial efficiency. In patients with coronary artery disease, structured aerobic exercise leads to significant increases in exercise tolerance and metabolic capacity, often exceeding gains observed after revascularization alone (Hambrecht et al., 2004). Improvements in cardiorespiratory fitness translate into prognostic benefit, reinforcing the importance of systematic post-PCI conditioning rather than reliance on procedural success alone.

Resistance training, once approached cautiously in coronary patients, is now recognized as a safe and beneficial adjunct to aerobic exercise when appropriately supervised. It enhances muscular strength, insulin sensitivity, and functional independence, particularly in older adults. Contemporary guidelines endorse combined aerobic and resistance training to optimize global functional recovery and facilitate return to occupational and recreational activities.

However, participation and adherence remain suboptimal worldwide; observational evidence suggests that fewer than half of eligible patients enroll in cardiac rehabilitation and dropout rates often exceed 30–50% within the first year of program initiation (Serves et al., 2023). This attrition significantly limits the durability of functional gains achieved during supervised training. Moreover, although many patients report adequate levels of physical activity following PCI, objective assessments using accelerometry frequently reveal considerably lower real-world activity than self-declared estimates, underscoring the importance of structured follow-up and objective monitoring strategies (Lee et al., 2023).

Together, these findings highlight that procedural success and initial rehabilitation enrollment do not automatically translate into sustained lifestyle modification. Contemporary PCI strategies may indirectly influence rehabilitation participation. Reduced procedural complications, shorter hospital stays, radial access, and abbreviated dual antiplatelet therapy (DAPT) regimens create a more favorable clinical trajectory for early enrollment in CR programs. Improved safety profiles may reduce patient anxiety regarding exercise-induced ischemia or bleeding risk, thereby supporting greater confidence in physical training.

Nevertheless, technology alone does not guarantee behavioral change. Structured referral systems, multidisciplinary follow-up, and personalized exercise prescriptions remain decisive determinants of long-term adherence. In the era of advanced drug-eluting stents, optimal functional recovery depends not only on durable revascularization but also on sustained engagement in structured and objectively monitored physical activity programs.

4.4. Long-Term Physical Activity After Contemporary PCI

Sustained physical activity following percutaneous coronary intervention (PCI) is a critical determinant of long-term cardiovascular prognosis. While procedural success and early rehabilitation improve short-term functional capacity, maintenance of health-promoting behaviors over time ultimately shapes clinical outcomes. Regular moderate-to-vigorous physical activity is associated with reduced recurrent ischemic events, improved metabolic control, and lower cardiovascular mortality in patients with coronary artery disease (CAD) (Kodama et al., 2009).

Despite these benefits, long-term adherence to exercise remains challenging. Although participation in cardiac rehabilitation (CR) is associated with improved survival and functional outcomes, sustained engagement in structured programs and maintenance of lifestyle modification beyond the supervised phase are inconsistent across populations (Doll et al., 2015). The transition from supervised rehabilitation to self-directed physical activity represents a vulnerable period, during which reductions in exercise frequency and intensity may occur. This pattern reflects multifactorial influences, including reduced professional supervision, competing life demands, and persistent psychological barriers. Accordingly, durable functional recovery depends not only on initial rehabilitation exposure but also on long-term behavioral support strategies designed to promote continued physical activity.

Return to sport represents an increasingly relevant issue, particularly among younger or recreationally active individuals undergoing contemporary PCI. Current expert consensus documents in sports cardiology support individualized evaluation, with gradual resumption of moderate-intensity exercise once ischemia is controlled and ventricular function is stable (Pelliccia et al., 2020). High-intensity competitive sports require careful risk stratification, particularly in patients with complex coronary anatomy or residual ischemia. Advances in contemporary drug-eluting stent (DES) technology, characterized by lower rates of stent thrombosis and target lesion failure, provide improved procedural stability; however, clearance for vigorous sport remains guided by global cardiovascular risk assessment rather than stent platform characteristics alone.

Psychological determinants play a substantial role in long-term activity patterns. Fear of recurrent cardiac events, symptom misinterpretation, and reduced confidence in physical resilience may limit exercise participation even in clinically stable individuals. Patient-reported outcome measures, such as the Seattle Angina Questionnaire (SAQ), have demonstrated that symptom burden and perceived functional limitation strongly influence quality of life and activity engagement (Spertus et al., 1995). Furthermore, studies in behavioral cardiology indicate that cardiac anxiety and illness perceptions are independently associated with reduced physical activity and poorer health-related quality of life after coronary events (Tully et al., 2016).

In the era of contemporary PCI, durable functional recovery therefore extends beyond anatomical revascularization. Long-term physical activity maintenance requires integration of procedural safety, structured rehabilitation, psychological reassurance, and ongoing behavioral reinforcement to translate technological progress into sustained lifestyle modification.

5. Mechanisms connecting DES with functional recovery

5.1. Vascular Stability and Tolerance to Hemodynamic Stress

Vascular stability after contemporary percutaneous coronary intervention (PCI) is a key determinant of safe functional recovery and tolerance to hemodynamic stress during physical exertion. Advances in drug-eluting stent (DES) design—including thinner struts, improved polymer biocompatibility, and optimized drug-release kinetics—have significantly enhanced vascular healing compared with first-generation platforms (Byrne et al., 2015).

Endothelialization represents a critical biological process following stent implantation. Delayed arterial healing and incomplete endothelial coverage were identified as central mechanisms underlying late stent thrombosis in early-generation DES (Joner et al., 2006). Pathological analyses demonstrated persistent fibrin deposition and inflammatory cell infiltration surrounding polymer-coated struts in first-generation devices. In contrast, newer-generation DES with more biocompatible or biodegradable polymers have been associated with more favorable healing patterns and reduced chronic inflammatory response in preclinical and imaging studies (Otsuka et al., 2015). Improved endothelial coverage reduces thrombogenicity and enhances vascular compatibility during conditions of increased shear stress.

From a clinical perspective, these biological improvements translate into lower rates of stent thrombosis and target lesion failure observed with contemporary DES compared with earlier devices or bare-metal stents (Bangalore et al., 2012). Such enhanced vessel stability is particularly relevant during physical activity, when heart rate, blood pressure, and coronary flow increase substantially.

During exercise, coronary blood flow must augment proportionally to myocardial metabolic demand. In successfully revascularized vessels with preserved endothelial recovery and minimal residual stenosis, coronary flow reserve can improve after PCI, thereby supporting higher workloads and improved exercise tolerance. Nevertheless, restoration of epicardial patency does not necessarily normalize microvascular dysfunction, which may persist in selected patients.

Thus, contemporary DES platforms provide a structurally and biologically more stable vascular environment, forming a mechanistic foundation for safe exposure to hemodynamic stress during progressive physical training.

5.2. Thrombotic and Bleeding Risk During Physical Exertion After PCI

Intensive physical exertion induces complex hemostatic changes that may transiently influence thrombotic and bleeding risk. Acute vigorous exercise is associated with increased platelet activation, elevated catecholamine levels, and enhanced shear stress, all of which may transiently promote a prothrombotic milieu (Mittleman et al., 1993). In patients with stable coronary anatomy and adequate endothelial recovery after contemporary PCI, these physiological responses are generally well tolerated. However, during the early post-procedural phase—particularly before complete endothelialization—theoretical concerns regarding stent thrombosis historically contributed to cautious recommendations on high-intensity exertion.

The introduction of newer-generation drug-eluting stents (DES), characterized by improved healing profiles and lower rates of late and very late stent thrombosis, has substantially mitigated this risk (Byrne et al., 2015). Nevertheless, antithrombotic management remains central to risk modulation. Dual antiplatelet therapy (DAPT) reduces thrombotic events after PCI but simultaneously increases bleeding risk, particularly during trauma-prone or high-impact physical activity (Valgimigli et al., 2018).

In physically active individuals, clinical decision-making must therefore balance thrombotic protection against hemorrhagic risk. Contemporary evidence supporting shorter DAPT regimens in selected patients provides an opportunity to individualize antithrombotic therapy. Such strategies may facilitate safer participation in structured and even higher-intensity exercise once vascular stability has been established.

5.3. Ischemia Reduction and Improvement in Exercise Capacity

Relief of myocardial ischemia represents a central mechanism through which percutaneous coronary intervention (PCI) may improve exercise tolerance. Coronary flow reserve (CFR) reflects the capacity of the coronary circulation to augment perfusion during increased metabolic demand. In the presence of flow-limiting stenosis, exercise-induced ischemia develops when myocardial oxygen demand exceeds supply. Successful revascularization restores epicardial patency and improves hyperemic flow, thereby increasing CFR and delaying ischemic threshold during exertion (Pijls et al., 1996).

The physiological importance of lesion-specific ischemia has been established in randomized trials of fractional flow reserve (FFR)-guided PCI. The FAME trial demonstrated improved clinical outcomes with FFR-guided compared with angiography-guided PCI (Tonino et al., 2009), while FAME 2 showed superiority of FFR-guided PCI over optimal medical therapy alone in selected patients with hemodynamically significant stenoses (De Bruyne et al., 2012). Although these trials primarily evaluated clinical endpoints rather than exercise performance, relief of ischemia has been associated with improvements in angina burden and functional capacity in studies assessing structured exercise and revascularization strategies (Hambrecht et al., 2004).

Nevertheless, the relationship between ischemia reduction and overall cardiorespiratory fitness is not strictly linear. Microvascular dysfunction, ventricular compliance, and peripheral conditioning independently influence exercise performance. Thus, while contemporary PCI enhances coronary flow dynamics and mitigates exertional ischemia, optimal gains in exercise capacity require integration with structured rehabilitation.

5.4. Psychological Implications of Contemporary Stent Technology

Beyond physiological stabilization, contemporary drug-eluting stent (DES) technology may exert indirect psychological effects that influence functional recovery after percutaneous coronary intervention (PCI). Improvements in stent safety profiles—characterized by lower rates of late stent thrombosis and reduced need for repeat revascularization—can contribute to greater perceived procedural durability and clinical reassurance (Byrne et al., 2015). A strengthened perception of cardiovascular stability may facilitate patient confidence during gradual reintroduction of physical activity. However, evidence directly linking stent platform characteristics to patient-reported psychological outcomes remains limited.

Fear of recurrent ischemia or exercise-induced cardiac events represents a well-recognized barrier to sustained physical engagement after coronary interventions. Cardiac anxiety and heightened symptom vigilance have been associated with reduced activity levels and impaired quality of life (Tully et al., 2016). Although technological advances do not directly eliminate psychological distress, improved procedural outcomes and clearer evidence regarding safety during rehabilitation may help mitigate kinesiophobia when appropriately communicated within multidisciplinary care.

Thus, in the era of contemporary PCI, psychological recovery should be viewed as complementary to anatomical and physiological restoration. Optimal functional outcomes require not only vascular stability but also targeted reassurance, education, and behavioral support to reduce fear-related avoidance of physical exertion.

5.5. Interaction With Cardiac Rehabilitation

Contemporary percutaneous coronary intervention (PCI), supported by improved drug-eluting stent (DES) platforms and optimized antiplatelet strategies, provides a safer clinical substrate for participation in supervised cardiac rehabilitation (CR). Exercise-based CR has consistently demonstrated a favorable safety profile, with very low rates of adverse cardiovascular events during monitored training sessions (Anderson et al., 2016). The combination of enhanced vascular stability and structured medical supervision allows for progressive increases in exercise intensity while maintaining procedural safety. Thus, modern PCI does not replace rehabilitation but reinforces its feasibility, enabling safe, individualized training as an integral component of functional recovery. While supervised rehabilitation is intrinsically safe, the improved stability of contemporary PCI may further support early and progressive exercise implementation.

6. Special populations

6.1. Patients at High Bleeding Risk

Patients at high bleeding risk (HBR) represent a particularly vulnerable subgroup in whom the balance between ischemic protection and hemorrhagic complications is critical. Advances in contemporary drug-eluting stent (DES) platforms have enabled safe shortening of dual antiplatelet therapy (DAPT) in this population. Randomized trials such as LEADERS FREE demonstrated that a polymer-free drug-coated stent combined with only one month of DAPT was superior to bare-metal stents with respect to safety and efficacy endpoints in HBR patients (Urban et al., 2015). Similarly, the MASTER DAPT trial showed that abbreviated DAPT followed by single antiplatelet therapy was non-inferior to standard-duration DAPT for ischemic outcomes and reduced major bleeding (Valgimigli et al., 2021).

From the perspective of physical activity, reduced bleeding risk has important practical implications. Shorter DAPT minimizes the hazard of exercise-related bleeding complications, particularly in elderly individuals and those participating in resistance or higher-intensity training. Although structured cardiac rehabilitation remains safe across risk groups, tailoring exercise intensity in HBR patients should consider residual hemorrhagic risk, comorbidities, and overall frailty. Contemporary PCI strategies may facilitate earlier mobilization and participation in supervised exercise while maintaining a favorable safety profile. This individualized approach supports functional recovery without compromising bleeding safety.

6.2. Older Adults

Older adults constitute a growing proportion of patients undergoing percutaneous coronary intervention (PCI). In this population, frailty, multimorbidity, and reduced physiological reserve significantly influence functional recovery. Frailty has been independently associated with worse cardiovascular outcomes, prolonged hospitalization, and reduced exercise capacity after revascularization (Afilalo et al., 2013). Therefore, procedural success alone does not guarantee restoration of functional independence.

Contemporary drug-eluting stents (DES) with improved safety profiles and the possibility of shortened dual antiplatelet therapy regimens are particularly advantageous in elderly individuals, who often meet criteria for high bleeding risk. However, tolerance to physical exertion in this group is frequently limited not only by residual ischemia but also by sarcopenia, deconditioning, and impaired autonomic regulation. Importantly, structured cardiac rehabilitation has demonstrated meaningful improvements in exercise capacity and quality of life even among older patients, although referral and participation rates remain suboptimal (Anderson et al., 2016).

Thus, in elderly populations, the clinical objective extends beyond preventing target lesion failure or major adverse cardiovascular events. Modern PCI should be integrated with individualized rehabilitation strategies that account for frailty status and baseline functional performance. Such an approach maximizes gains in mobility, autonomy, and long-term physical activity while maintaining procedural safety.

6.3. Patients with Diabetes

Diabetes mellitus represents one of the most important comorbidities affecting outcomes after percutaneous coronary intervention (PCI). Patients with diabetes exhibit a higher risk of restenosis, diffuse atherosclerosis, and impaired vascular healing compared with non-diabetic individuals. These pathophysiological factors historically limited the long-term efficacy of both bare-metal stents and early-generation drug-eluting stents. However, contemporary DES platforms using improved antiproliferative agents and thinner strut designs have significantly reduced rates of target lesion failure and repeat revascularization in this high-risk population (Kedhi et al., 2010; Bangalore et al., 2012).

Beyond procedural outcomes, diabetes also influences functional recovery and exercise capacity. Metabolic dysfunction, endothelial impairment, and peripheral insulin resistance may attenuate improvements in aerobic capacity following revascularization. Nevertheless, structured exercise training remains a cornerstone of secondary prevention in patients with diabetes and coronary artery disease. Cardiac rehabilitation programs have been shown to improve glycemic control, endothelial function, and cardiorespiratory fitness, which together contribute to improved long-term prognosis (Balady et al., 2007). Consequently, integrating contemporary PCI with supervised rehabilitation is particularly important in diabetic patients to optimize both vascular outcomes and functional recovery.

6.4. Physically Active Patients and Athletes

A growing proportion of patients undergoing percutaneous coronary intervention (PCI) remain physically active and seek to resume recreational or competitive sports after revascularization. Contemporary drug-eluting stent (DES) technology, characterized by improved vascular healing and lower rates of stent thrombosis, may facilitate an earlier and safer return to structured physical activity. Nevertheless, return-to-sport decisions should be individualized and guided by clinical stability, absence of inducible ischemia, and adequate completion of cardiac rehabilitation programs (Pelliccia et al., 2020).

An important consideration in physically active patients is the management of dual antiplatelet therapy (DAPT). While DAPT significantly reduces thrombotic risk after PCI, it simultaneously increases the potential for bleeding, which may be particularly relevant in contact or trauma-prone sports. Current expert recommendations therefore suggest temporary restriction from high-risk athletic activities during the mandatory DAPT period, with gradual return to full participation after therapy de-escalation and careful clinical evaluation (Pelliccia et al., 2020; Levine et al., 2016). In this context, advances in DES safety and the possibility of shorter DAPT regimens may indirectly facilitate earlier resumption of athletic activity while maintaining procedural safety.

7. Clinical implementation

7.1. The "PCI-to-Rehabilitation" Pathway

Optimal functional recovery after percutaneous coronary intervention (PCI) requires integration of interventional treatment with structured secondary prevention strategies. In this context, a coordinated "PCI-to-rehabilitation pathway" has been proposed as a practical model to bridge acute revascularization with long-term functional recovery. Such a model emphasizes early multidisciplinary collaboration between interventional cardiologists, cardiac rehabilitation specialists, and—when relevant—sports medicine physicians. This multidisciplinary approach enables comprehensive assessment of cardiovascular stability, exercise tolerance, and individual risk factors before progression to higher levels of physical activity (Balady et al., 2007; Pelliccia et al., 2020).

Early referral to cardiac rehabilitation represents a key component of this pathway. Evidence consistently demonstrates that patients referred to rehabilitation shortly after hospital discharge are more likely to enroll, adhere to exercise programs, and achieve meaningful improvements in cardiorespiratory fitness and cardiovascular risk profiles (Anderson et al., 2016). Contemporary PCI techniques, including safer drug-eluting stent platforms and improved antiplatelet management, may facilitate earlier mobilization and clinical stabilization, thereby creating favorable conditions for prompt rehabilitation initiation. When effectively implemented, the PCI-to-rehabilitation pathway may facilitate functional recovery, improve long-term physical activity patterns, and enhance overall patient-centered outcomes following coronary revascularization.

7.2. Exercise Prescription After PCI

Exercise prescription following percutaneous coronary intervention (PCI) should be individualized and structured according to the FITT principle—frequency, intensity, time, and type of exercise. Current cardiac rehabilitation guidelines recommend initiating supervised aerobic training in the early post-discharge period, typically 3–5 sessions per week, at moderate intensity corresponding to approximately 40–70% of peak oxygen uptake (VO_2peak) or 11–14 on the Borg Rating of Perceived Exertion scale (Balady et al., 2007; Visseren et al., 2021). Exercise duration generally ranges from 20-60 minutes per session and may include walking, cycling, or other rhythmic endurance activities.

Gradual progression of training load is essential to ensure safety and optimize functional recovery. Early rehabilitation programs typically emphasize moderate-intensity aerobic exercise, followed by the introduction of resistance training after clinical stabilization and adequate vascular access site healing. Progressive increases in exercise intensity and duration should be guided by symptom monitoring, functional testing, and clinical evaluation.

Evidence from large meta-analyses indicates that participation in exercise-based cardiac rehabilitation improves quality of life and reduces cardiovascular hospitalizations in patients with coronary heart disease (Anderson et al., 2016). Contemporary prevention guidelines further emphasize that early referral to structured rehabilitation following coronary revascularization, including PCI, is a key component of secondary prevention and facilitates safe restoration of physical activity and cardiorespiratory fitness (Visseren et al., 2021).

7.3. Integration with Clinical Guidelines

Contemporary clinical guidelines emphasize that structured physical activity and participation in cardiac rehabilitation constitute central components of secondary prevention following percutaneous coronary intervention (PCI). Both European and North American cardiovascular societies recommend early referral to rehabilitation programs as a standard element of post-revascularization care. The European Society of Cardiology guidelines on cardiovascular disease prevention highlight that supervised exercise training improves functional capacity, reduces recurrent cardiovascular events, and facilitates the long-term adoption of healthy lifestyle behaviors (Visseren et al., 2021). Similarly, the American College of Cardiology and American Heart Association emphasize that cardiac rehabilitation and structured exercise prescription should be integrated into comprehensive secondary prevention strategies for patients with coronary artery disease (Smith et al., 2011).

Within these frameworks, physical activity is not considered merely an adjunct intervention but a core therapeutic modality that complements pharmacological treatment, revascularization procedures, and risk-factor modification. Importantly, modern PCI techniques and improved drug-eluting stent technologies have contributed to enhanced procedural safety and clinical stability, thereby enabling earlier initiation of rehabilitation and more effective restoration of functional capacity. Integrating interventional cardiology outcomes with structured rehabilitation pathways therefore represents a key strategy for optimizing long-term recovery and cardiovascular health after PCI.

8. Limitations of Current Evidence

Despite substantial progress in interventional cardiology and cardiac rehabilitation research, several important limitations remain in the current evidence base linking modern percutaneous coronary intervention (PCI) technologies with functional recovery and long-term physical activity outcomes. Most clinical trials evaluating drug-eluting stents (DES) primarily focus on traditional cardiovascular endpoints such as target lesion failure, myocardial infarction, or major adverse cardiovascular events. Consequently, randomized controlled trials directly examining the relationship between specific stent generations and objective indicators of exercise performance—such as peak oxygen uptake (VO_2peak), metabolic equivalents (METs), or the six-minute walk test—are limited. This creates a relative evidence gap between technological advances in PCI and their direct evaluation using standardized functional performance measures (Neumann et al., 2019).

In addition, many available studies include relatively short follow-up periods, typically ranging from several months to one year after revascularization. While these time frames are sufficient to evaluate early procedural outcomes and short-term improvements in exercise tolerance, they provide more limited insight into the long-term sustainability of lifestyle changes and physical activity patterns following PCI.

Another limitation is the considerable heterogeneity in how physical activity and functional recovery are defined and measured across studies. Some investigations rely on self-reported questionnaires assessing leisure-time or habitual physical activity, whereas others employ objective methods such as accelerometry, wearable activity monitors, or cardiopulmonary exercise testing. Each approach captures different dimensions of physical performance and is subject to distinct methodological limitations, including recall bias in self-reported measures and variability in device-based monitoring protocols. As a result, direct comparison of physical activity outcomes across studies can be challenging, and synthesis of results across heterogeneous methodologies remains limited (Prince et al., 2008; Troiano et al., 2014).

Finally, there is a notable lack of evidence addressing highly active individuals or competitive athletes undergoing coronary revascularization. Most clinical trials and rehabilitation studies focus on general or older coronary artery disease populations, leaving uncertainty regarding optimal exercise recommendations, training intensity limits, and antiplatelet management strategies for patients returning to high-performance sport. Current sports cardiology guidelines acknowledge that evidence in this area remains limited and that many recommendations rely on expert consensus rather than randomized data (Pelliccia et al., 2020). Addressing these knowledge gaps will require future research integrating perspectives from interventional cardiology, exercise physiology, and sports cardiology.

9. Future Research Directions

Despite major technological advances in contemporary drug-eluting stents (DES), the impact of these innovations on functional recovery after percutaneous coronary intervention (PCI) remains insufficiently investigated. One important direction for future research involves direct comparisons between modern thin-strut DES and earlier generations of stents with regard to exercise capacity, tolerance to physical exertion, and the time required for patients to return to regular physical activity. Most randomized trials evaluating coronary stents have primarily focused on traditional clinical endpoints such as target lesion failure, restenosis, and stent thrombosis. Although these outcomes are crucial for assessing procedural safety and long-term vessel patency, functional outcomes such as exercise capacity and daily activity levels remain relatively underreported in the PCI literature (Bangalore et al., 2012; Palmerini et al., 2015). Future investigations incorporating cardiopulmonary exercise testing (CPET), maximal oxygen uptake (VO_2max), and standardized physical activity assessments could provide a more comprehensive understanding of patient recovery following PCI.

Another promising research direction concerns the identification of biomarkers reflecting vascular healing after stent implantation. Markers of endothelial recovery, inflammatory response, and platelet activation may offer valuable insight into the biological processes underlying post-procedural recovery and may help determine when it is safe for patients to resume higher levels of physical exertion. Integrating biomarker analysis with advanced intracoronary imaging techniques could further clarify the relationship between vascular healing and the hemodynamic stress associated with physical activity following coronary interventions (Kereiakes et al., 2016).

Future studies should also explore the role of digital health technologies in monitoring physical activity among patients after PCI. Wearable devices capable of tracking daily steps, heart rate, heart rate variability, and exercise intensity may provide objective real-world data on recovery trajectories and adherence to rehabilitation programs. Such monitoring could complement conventional cardiac rehabilitation strategies and support clinicians in evaluating long-term lifestyle modification and cardiovascular risk management (Piotrowicz et al., 2016; Anderson et al., 2016).

Finally, further research should investigate the potential for personalization of dual antiplatelet therapy (DAPT) in relation to patients' physical activity levels and bleeding risk. Individualized antithrombotic strategies that take into account thrombotic risk, bleeding risk, and expected physical activity patterns may enable safer participation in exercise and sports following PCI. Tailoring the duration and intensity of DAPT could therefore become an important component of patient-centered secondary prevention strategies (Valgimigli et al., 2018; Visseren et al., 2021).

10. Final Conclusions

Over the past two decades, technological progress in drug-eluting stents has substantially improved the safety and effectiveness of percutaneous coronary interventions. Contemporary DES, characterized by thinner struts, improved polymer biocompatibility, and optimized drug-elution kinetics, have been consistently associated with lower rates of restenosis and stent thrombosis compared with earlier stent generations (Bangalore et al., 2012; Palmerini et al., 2015).

Although most clinical trials evaluating PCI have focused on traditional procedural and angiographic outcomes, emerging evidence suggests that the improved safety profile of modern DES may indirectly facilitate a safer and earlier return to physical activity. Enhanced endothelial healing, reduced inflammatory response, and lower thrombotic risk may create favorable conditions for participation in structured cardiac rehabilitation and the gradual resumption of exercise following revascularization.

At the same time, current literature highlights the need for greater integration of functional outcome measures in studies assessing PCI effectiveness. Parameters such as exercise tolerance, physical activity levels, quality of life, and time required to return to work or sport may better reflect real-world recovery and patient-centered outcomes than procedural endpoints alone (Anderson et al., 2016; Visseren et al., 2021).

Exercise-based cardiac rehabilitation remains a cornerstone of secondary prevention in patients with coronary artery disease. Robust evidence demonstrates that participation in rehabilitation programs is associated with reduced cardiovascular mortality, fewer hospitalizations, and improved quality of life (Anderson et al., 2016). Consequently, advances in PCI technology provide an opportunity to strengthen the connection between interventional cardiology and exercise-based rehabilitation, enabling patients to restore functional capacity more effectively after coronary revascularization.

Looking ahead, closer integration between interventional cardiology, sports medicine, and digital health technologies may play an important role in optimizing recovery after PCI. The incorporation of wearable activity monitoring, personalized rehabilitation protocols, and individualized antiplatelet therapy strategies may further improve long-term outcomes. Ultimately, the continued evolution of stent technology combined with comprehensive rehabilitation approaches has the potential not only to improve survival but also to enhance functional recovery and long-term physical activity levels in patients undergoing PCI (Piotrowicz et al., 2016; Valgimigli et al., 2018).

Disclosure

Author's Contribution:

Conceptualization: Justyna Czechowicz, Zuzanna Kruczek, Dorota Kołkowicz

Methodology: Justyna Czechowicz, Julia Kociuba, Natalia Pawełczak

Software: Mikołaj Antkiewicz, Julia Kociuba, Agata Krawczyk

Check: Paweł Czechowicz, Aleksandra Arczyńska-Antkiewicz, Maria Drozd
Formal analysis: Paweł Czechowicz, Zuzanna Kruczek, Natalia Pawełczak
Investigation: Mikołaj Antkiewicz, Julia Kociuba, Martyna Kudła
Resources: Justyna Czechowicz, Zuzanna Kruczek
Data curation: Mikołaj Antkiewicz, Dorota Kołkowicz, Martyna Kudła
Writing–rough preparation: Paweł Czechowicz, Agata Krawczyk, Paulina Łobaza
Writing-review and editing: Justyna Cechowicz, Natalia Pawełczak, Paulina Łobaza
Visualization: Aleksandra Arczyńska-Antkiewicz, Maria Drozd
Supervision: Aleksandra Arczyńska-Antkiewicz, Maria Drozd, Dorota Kołkowicz
Project administration: Justyna Czechowicz

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